Libyan Arab Republic

Kufra Agricultural Company

Jalu – Tazerbo Project: Phase 1

INTERIM REPORT

Hydrogeological Department
Institute of Geological Sciences
Exhibition Road
London SW7 2DE

1973

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by

E. P. Wright

with contributions by

A. C. Benfield, W. M. Edmunds, R. Kitching

12 APPENDIXES

by

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NB Maps related to the report are available from Dr. E. Wright

The Institute of Geological Sciences was formed by the incorporation of the Geological Survey of Great Britain and the Museum of Practical Geology with Overseas Geological Surveys and is a constituent body of the Natural Environment Research Council

Printed in England for the Institute of Geological Sciences
by North London Offset Services Limited

IGS 661 50 3/73

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Interim Report

1. INTRODUCTION

1.1. FOREWORD

1.1.1. Jalu - Tazerbo Project: Programme

The Institute of Geological Sciences commenced its investigations on the 18th of May 1971 on behalf of the Libyan Government. These investigations were designed to be concentrated in two areas of Central Cyrenaica scheduled for potential development and designated in this report as the Phase One (1) and Phase Two (2) Areas, (Map Figure 1). This Interim Report will provide the essential data and main conclusions of the study of the Phase 1 Area, and the information should be sufficient to form the basis of a development programme, should this be proposed. A final report dealing in detail with more specific aspects of the study will be presented later in 1973. These aspects will be referred to in the present document, but as study on them is continuing, a fuller discussion is being deferred.

The test drilling programme associated with these investigations commenced in December 1971 and it was anticipated would continue until August 1973. In the event, the drilling programme has been subject to considerable delay and it is unlikely to be concluded before December 1973. The reports on the Phase 2 Area will be presented some 4/5 months after drilling and aquifer testing have been completed, although interim reports may be prepared at an earlier date if required.

1.1.2. The Implementation of the Studies

As well as investigations in the field areas, studies were also carried out in Tripoli and Benghazi, mainly to obtain and abstract data from oil company records. Work in the U.K. has included geochemical analysis, general data synthesis model and map preparation and the writing of reports.

The Project has been arranged and carried out under the general control and guidance of Mr D.A. Gray, Chief Hydrogeologist of the Institute of Geological Sciences. The main study team was composed of the following personel, under the control of the Project Leader, Dr E.P. Wright. Aspects on which individuals made specialised studies are shown in brackets.

		Weeks*
Dr E.P. Wright	Principal Scientific Officer: Project Leader	32
Dr R. Kitching	Principal Scientific Officer (Physicist/ model study)	-
Mr A.C. Benfield	Senior Scientific Officer (Stratigraphy/sedimentology)	10
Dr W.M. Edmunds	Senior Scientific Officer (Geochemistry)	11
Mr K.H. Murray	Senior Scientific Officer	40
Mr M. Price	Higher Scientific Officer	31
Mr I.B. Harrison	Higher Scientific Officer	4
Mr J. Black	Scientific Officer	29
Mr I. Gale	Scientific Officer	24
Mr P.J. Chilton	Scientific Officer	10
Mr D.R. Giddings	Scientific Officer (Analyst)	-
Mr J. Shedlock	Scientific Officer	5
Mr T.R. Shearer	Scientific Officer	-
Mr P. Hillyard	Assistant Scientific Officer	7
Mr J. Worth	Temporary Scientific Officer (Analyst)	-

* Period of time spent in Libya between May 1971 and March 1973.

1.1.3. Acknowledgements

These studies were carried out in collaboration with the Kufra Agricultural Company to which the Institute was directly responsible. Apart from local organisations, administration and general planning, this Company also provided additional qualified hydrogeological personnel to assist the Institute in its field investigations. These have included:-

1. Mr S.M. Hasanayn

2. Mr F. Zubairi

3. Mr S. Ahmed

The Institute wishes to acknowledge the extensive assistance provided by the Company in all stages of the investigations and in particular wishes to express its appreciation to Mr M.A. Karah, Director General of the Company and Mr A.L. Craig, Chief Engineer.

The Institute also wishes to acknowledge the assistance of various oil companies who provided information, notably maps, well logs etc., as well as, in some cases, practical assistance in the field areas and office facilities in Tripoli or Benghazi. These companies included the following:

Amoco

Amoseas

Arabian Gulf Oil Company

Aquitaine

Circle Oil Company

Elwerath/Wintershall

Esso Standard (Libya) Inc

Libya Shell N.V.

Mobil Oil

National Oil Company of Libya

Oasis Oil Company

Occidental

Union Rheinishe

1.2. OBJECTIVES AND SCOPE

At the commencement of the studies, the overall objectives were as follows:-

1. Within selected areas of Central Cyrenaica to determine the occurrence, depth and extent of fresh groundwater zones.

2. To establish the magnitude and variations of the aquifer constants in these areas.

3. To assess the long term potential yields of these aquifers and to produce a set of overall criteria covering the design, construction, operation and control of required production wells. Two irrigation projects were to be considered, one in the Jalu Area (Phase 1) and the second in the region to the south between Sarir and Tazerbo (Phase 2). Also under consideration was the possibility of supplying water to the Agedabia coastal region.

1.2.1. The Phase 1 Area: Planning

Initial planning proposed an irrigation project extending over 2000 hectares to be sited in an area where soil and water availability provided optimum conditions. The area selected after the preliminary survey lay to the south and south-east of Occidental 103 - D Field and the initial test drilling sites were selected with this proposal in mind. The supply of water to Agedabia was not strictly defined in quantitative terms, and initial studies were concerned with determining the northern limits of water of adequate quality in order to assess minimum pumping distance requirements.

A change of emphasis occurred in mid-1972 and requirements were greatly enlarged. The possibility of piping water not only to coastal areas but also for irrigation was given consideration. For this reason, detailed investigations were extended over the main area underlain by good quality water with exploratory drilling and testing occurring in outlying areas mainly in order to evaluate boundary conditions and possible long-term effects.

Current planning now envisages a supply of 180 000 m^3/day (annual rate of 153 000 m^3/day) for water supply to Agedabia and associated coastal areas, as part of a larger scheme in which a further 820 000 m^3/day (annual rate of 697 000 m^3/day) will be provided from regions farther south.

1.2.2. The Phase 2 Area: Planning

An irrigation project for 50 000 hectares is proposed requiring some $2\frac{1}{2}$ million m^3/day of water located mainly in the north-central Phase 2 Area. A drilling contract for 500 production wells for this scheme has already been let on the basis of existing data but as drilling cannot commence for several months and will continue for several years, the findings of the Phase 2 investigations will become relevant at an early stage as well as for longer term implementations or modifications. Additional requirements for the Phase 2 Area include potential schemes in the southern (Tazerbo/Bu Zerraigh) districts, and possible contributions by piping water to both the Agedabia and Tobruk areas. A supply of a million m^3/day is envisaged for the latter.

2. HYDROGEOLOGY OF THE PHASE 1 AREA

2.1. GENERAL FEATURES

2.1.1. Extent

The study area extends over some 38 000 sq km and its location is shown on Map Figure 1 and other maps which accompany this report. Drilling investigations were limited to a central section and the model study was restricted to the Post-Middle Miocene aquifer which underlays about two thirds of the Phase 1 Area in the centre and east.

2.1.2. Physiography and Climate

The land surface of the Phase 1 Area is largely composed of 'sarir', flat or gently undulating terrain covered by coarse sand or gravel. Transitional finer grained sands which border the Calanscio dune sands occur on the eastern border. The regional topography is shown in Map Figure 1, taken from an earlier report (Wright and Edmunds, 1969). The regional depression shown on this map is not a marked topographic feature on the ground surface but must have exercised some control on hydrographic development and probably also on the development and location of the recent dune sands. It is significant that similar-trending features are also apparent on the larger-scale topographic map of the Phase 1 Area (Map Figure 2). Smaller-scale wadi dissection commonly follows the same general trends but individual valley lines have insufficient relief to be apparent on the map. Dissected terrain is most marked to the north of latitude 29° N and in the south and south-west. The terrain in the centre and south-east tends to be more uniform and featureless. Perennial vegetation, including such trees as palms and acacias, is mainly limited to the vicinity of the oases and along prominent wadi lines, but temporary grassy growths following rainfall have a wide extent.

Rock outcrops occur fairly commonly throughout the Phase 1 Area but most markedly in the south and west. The outcrops are generally of small extent and low lying in the 'sarir' terrain and commonly composed of limestones or calcretes. More extensive rocky outcrops, also of limestone, occur in the western scarp areas and on occasional, low, flat-topped hills to the south-east of Jalu oasis.

The climate is arid with an annual rainfall of negligible proportions. The prevailing winds are from the north-north-west to north with periodic strong southerly winds. Sand and dust storms (ghiblis) are commonly associated with rapidly changing wind directions. From general observations during the past year, sand movement is not noticeably to be correlated with the southerly winds although significant temperature rises are associated. In general the climate may be described as equable in the winter and not unduly hot in the summer except during the short periods of ghibli associated with southerly winds. Weather records are limited to the Jalu oasis and a summary of pertinent information is listed below:-

Years of Record	8 - 15
Precipitation Annual Average	0.5 inches
Air Temperatures °C	
Absolute maximum	49.1
Absolute minimum	-2.8
Mean maximum January	20.2
July	37.1
Mean minimum January	6.1
July	22.5
Windspeed knots	
Equal or exceeded	
80% of time	5
20%	9
5%	13
2%	16
0.1%	27

2.1.3. Population

Permanent settlements are limited to the Jalu and Augila oases and the total populations amount to a few thousand people. Temporary settlements occur at oil camps of which there are several in the Phase 1 Area. Locations of camps are shown on Map Figure 2.

2.2. INVESTIGATIONS

2.2.1. Previous Investigations

Previous hydrogeological investigations in this area are limited to those carried out by this Institute in 1967/68 and a list of the relevant reports and publication is given below. Reference has also been included to groundwater studies which include maps covering the whole of Libya.

1. EVERDINGEN, R.O. VAN. 1962. The deeper groundwater in Libya. Bull. Int. Ass. sci. Hyd. No. 3.

2. JONES, J.R. 1964. Groundwater maps of the Kingdom of Libya. Open File Rept. U.S. Geol. Surv.

3. WRIGHT, E.P. 1967. Interim report on the hydrological investigations carried out in Concessions 65 and 80 in Libya, between 9th October and 22nd December 1967. Unpub. Rep. for Brit. Petrol. Co. Ltd. Institute of Geological Sciences.

4. WRIGHT, E.P. 1968. Supplementary report to Wright, 1967.

5. WRIGHT, E.P. and EDMUNDS, W.M. 1969. Hydrogeological studies in central Cyrenaica. Unpub. Rept. for Brit. Petrol. Co. Ltd.

6. WRIGHT, E.P. and EDMUNDS, W.M. 1971. Hydrogeological studies in central Cyrenaica, Libya. Symposium on the Geology of Libya, Faculty of Science, University of Libya.

The investigations carried out in 1967/68 consisted of a regional appraisal of existing geological logs, combined with field measurements of water levels and electrical conductance in existing water wells. Samples were collected and subsequently analysed. Short duration (3 days) pumping tests were carried out at 6 existing groups of wells but the conditions of the tests were such as to make the results of dubious value. The overall results of the studies did show the existence of major aquifers of great potential value occurring within the post-Eocene formations in central Cyrenaica. The report noted that water of moderate to good quality occurred mainly to the south of latitude 28°N but had a northerly extending lobe to the west of Jalu oasis. It is in this area that the Phase 1 studies have been concentrated.

2.2.2. Current Investigations

The Phase 1 investigations commenced with a detailed appraisal of geological and hydrological file data followed by field surveys in existing water wells (conductance logging, well water levels, geochemical sampling, some gamma-ray logging etc). This information was required to supplement that acquired during the more regional studies carried out in 1967/68. On the basis of these initial studies and surveys, technical specifications were prepared for a programme of test drilling and aquifer testing (reference in list of reports at end of this section). The primary purpose of the test drilling was to obtain more comprehensive and accurate geological data than that already available as well as to determine the physical constants of the aquifers for model construction and predictive quantitative analysis. Representative lithological samples were collected throughout the aquifer and subsequently analysed in a variety of ways. Gamma-ray logs of test wells and associated existing water wells were run. At two sites of particular interest additional geophysical logs were obtained by Schlumberger. Aquifer testing using a production well and at least two observation wells was carried out at eleven test sites. Pumping was for 5-10 days duration during which accurate and detailed measurements were taken of discharge, drawdowns, field physico-chemical data on the discharge water etc. Samples were subsequently analysed for major, minor and trace mineral content.

The preliminary studies and surveys showed that in the Phase 1 Area, two aquifer systems required consideration:- an effectively single aquifer within Post-Middle Miocene (P.M.M.) formations which underlie the central and east Phase 1 Area; and a multiple aquifer system in the older Miocene and Oligocene strata. The older formations outcrop in the west and dip eastward below the Post-Middle Miocene, whose outcrop boundary trends approximately north-south [Map Figure 7]. The lobe of good quality water noted in the earlier studies occurs mainly within the P.M.M. aquifer. By virtue of its location close to existing population centres as well as to the presence of good quality water occurring at relatively shallow depths, the detailed investigations including test drilling were confined to the P.M.M. aquifer. No significant study has been carried out on the aquifers in the Miocene or Oligocene formations. Although some of these do have undoubted potential, it is unlikely that any development would be warranted prior to that of the more accessible P.M.M. aquifer.

The process of model development commenced with the preparation of a basic steady-state model. An unsteady-state model was subsequently derived to which various pumping schemes have been applied in order to predict subsequent performance of the aquifer. Two schemes have been applied to date and the results are shown in this report.

They are:-

1. A discharge of 328 000 m^3/day from eight centrally located well fields for periods up to 25 years.

2. A discharge of 153 000 m^3/day from a total of 33 individual wells spaced over the main central (1200 sq km) area underlain by good quality water.

The first scheme was in the nature of a trial using a moderately high pumping rate from a central location. The second scheme models in more practical terms the requirements proposed for the Agedabia supply from the Phase 1 Area and the well distribution is intended to maximise the water availability for a particular spacing.

A third scheme under current preparation will incorporate the requirements of a 10 000 hectare irrigation project (annual production requirements expressed as an average daily rate of 600 000 m^3.). The production wells will be located in two blocks 17 x 3 km which will be pumped until the predicted drawdowns reach the screened intervals. Water for subsequent irrigation use will need to be brought in from outside the two initial well fields.

The three schemes outlined above utilise a relatively simple set of boundary conditions which are thought to apply to the longer-term developments in the aquifer. The most significant condition is that which regards the aquifer as a single unconfined body. Testing has shown that where well screens are located below high-level clay layers, the aquifer behaves in leaky artesian fashion. The effect of this will be to increase drawdowns relative to the model predictions and will be of significance in well field spacing but may have less effect on regional drawdowns.

A final matter of concern in the longer-term effects will be water quality changes since there is a deterioration within the aquifer to the north and east of the Phase 1 Area. Both these features, i.e. leaky artesian effects and future water quality changes, will be considered in the Final Report, either within the model framework or by analysis.

List of significant file reports (date order)

1. E.P. WRIGHT, August 1971. Notes on a visit to the Jalu - Augila Area.

2. E.P. WRIGHT, August 1971. Technical specifications. Section IV in the Contract for drilling 28 production water wells and 36 observation wells/boreholes, executing pumping tests etc, in the Sirte Basin.

3. E.P. WRIGHT, October 1971. Hydrogeology of the Phase 1 Area.

4. A.C. BENFIELD, January 1972. Post-Oligocene sediments, Jalu region, Sirte Basin, Libya.

5. E.P. WRIGHT, September 1972. The Jalu - Tazerbo Project: current appraisal at end September 1972.

6. W.M. EDMUNDS, 1972. Carbon isotope investigations, Libyan Arab Republic. WD/ST/72/9.

7. W.M. EDMUNDS, 1972. Initial report on field analytical data on groundwater from the Jalu - Tazerbo Phase 1 Area. WD/ST/72/5.

8. R. KITCHING, April 1973. Report on groundwater model in the Jalu - Tazerbo Area, Libyan Arab Republic.

2.3. METHODS OF INVESTIGATION

2.3.1. Procedural Order

a. Abstraction of relevant data from existing records.

b. Measurement at existing well sites (field survey).

c. Test drilling and aquifer testing.

This procedure was adopted generally but circumstances did not always permit the most advantageous timing, and both data collection and existing site measurements extended into the test drilling period.

2.3.2. Existing Records

2.3.2.1. Hydrological

A large number ofwater wells have been drilled in Libya and the files in oil company offices record a limited amount of site data. Details of well depths, casing and perforation records are likely to be correct. Lithological data is only provided in most general terms if at all. Location and ground elevations are commonly those for an associated oil exploration well in connection with which the majority of water wells were drilled. Ground elevations are normally quoted to the nearest foot, and locations to a second of arc. Such values are presumably accurate within the limits quoted but confirmation is lacking. Rest water levels in wells are rarely given and if provided are likely to be very inaccurate (to with ±50 feet). Discharge rates except for wells designed for long-term production in oil-field areas, cannot be considered accurate to even a moderate degree. Pumping drawdowns are not normally recorded, even in production wells. Aquifer tests have not been carried out by any oil company other than those commissioned by British Petroleum Oil Co. during the Institute's previous investigations. Geochemical or physical data on the water discharge is limited but, when available, the results are likely to be reliable.

2.3.2.2. Geological

Lithological and stratigraphic data abstracted from the records of oil company wildcat and production boreholes. Attention was concentrated mainly on the near-surface post-Oligocene strata but some data were collected on the Oligocene sediments although these formations are not discussed in any detail in this report.

Each record comprises a variety of well logs which usually include a lithological log based on borehole cuttings and several types of geophysical log. In some cases an interpretation of the strata penetrated correlated with the Induction Electric Survey (IES), termed an IES Lithology Log, and a Final Log, which incorporates any palaeontological information and presents a detailed stratigraphy of the borehole, were also made available.

The problems associated with each log and its availability as regards the post-Eocene strata in the Phase 1 Area are discussed below:

1. Lithological Log: In addition to the usual problem of time lagging samples in rotary drilling, further problems result from the extreme rapidity with which the upper unconsolidated strata are penetrated. In many cases the upper 600 ft are drilled in less than one day, and even to depths as great as 1500 ft high drilling rates are maintained. This results in excessively long sample intervals - one to two hundred feet being common - and the production of only a very generalised log. In many instances, no lithological log was compiled for the first few hundred feet but thereafter the log is usually available.

2. IES: Two problems arise as regards the present investigation. First, as surface casing may be carried to around 500 ft or even deeper to penetrate the unconsolidated near-surface sands, no IES log is available until below this depth. Second, the low salinity of ground-water within the near-surface formations results in a self-potential (SP) log which shows almost no detail in this part of the section. IES logs are always available below the casing.

3. Borehole Compensated Sonic Log (BHS): This log is of course only available below the surface casing and even here the log may be of little value because of large borehole diameter. However in some cases a log has been found helpful in distinguishing between sands and limestones in the upper 1500 ft of the succession. Availability of the log is patchy over the Phase 1 Area and appears to depend on the type of oil reservoir being sought at depth.

4. Caliper: This is only available for the post-Eocene sediments in a small number of boreholes where it has proved to be a useful confirmatory log.

5. Gamma Ray (GR): Since this log can be run within a cased hole it has proved most valuable in the interpretation of the near-surface strata. Only where several strings of casing are present and cause excessive diminution of the tool signal, is the log unusable. Availability is fortunately quite good, though by no means all boreholes are

logged in this way.

6. Neutron Porosity Log: This log is generally run in conjunction with the GR and may in some cases provide a measure of confirmation of the other logs. Rather few boreholes in the Phase 1 Area have been logged in this way in their upper sections.

7. IES/Lithology Log: This interpretative log is often only compiled in rather generalised units in the upper 1500 ft of the borehole and obvious errors have been noted in some interpretations. Consequently for the purposes of the present study, it proved necessary to prepare or revise IES/ Lithology Logs of the post-Oligocene strata for a considerable number of boreholes.

8. Final Log: This log is only available for a limited number of boreholes. However, in many cases formation tops are picked on the IES/Lithology Logs and provide a most valuable source of stratigraphic information.

Data from the records of 180 boreholes were utilised in the present studies. Their locations are given on Map Figure 3 which also shows the boundaries of the oil company concessions. The density of the coverage of boreholes aimed at in this study was of the order of one per five minute rectangle. In some cases, the absence of information in adjacent rectangles led to the selection of a borehole record at the edge of an already sampled rectangle. In other cases, although a borehole had been drilled in a rectangle, the record proved to contain no information about the post-Oligocene sediments and it is this omission that accounts for the apparently unsampled but drilled rectangles.

In addition to the examination of subsurface records, an appraisal and synthesis of photo-geological map information was also carried out mainly in connection with the delimitation of the outcrop boundary between unconsolidated Post-Middle Miocene sediments and consolidated Miocene rocks.

2.3.3. Field Surveys

Field surveys consisted of measurements in existing water wells of water levels and electrical conductance, and the collection of a sample for later analysis. Gamma-ray logs were also run in a number of water wells. Except in isolated cases individual wells cannot be identified by oil company file number other than as one of the group numbers occurring at the site. Two or three water wells are commonly present at each oil exploration site. Measurements were recorded from casing or tubing tops and significant differences in ground elevation to the associated oil well are noted. A complete tabulation of all data will be presented in the final report.

2.3.3.1. Static Water Levels

Measured levels are recorded in units below ground level and above sea level. Wells in individual groups are commonly perforated at the same interval but where significant differences exist, measurements were made on the different wells in order to detect vertical head gradients. Measurements were made with an electric probe and should be accurate to a centimetre.

2.3.3.2. Specific Electrical Conductance Logs

These were run in at least one water well at each site, provided that a well was open down to the perforated interval. Existing wells on site were tested for depth but no log was run unless the perforated interval could be reached. Initial surveys utilised a rather coarse 'megger' measurement for which no temperature correction could be made. Later measurements were made with a more accurate bridge in which capacitance effects could be compensated and temperature recorded simultaneously. Tabulated results record apparent conductance, conductance corrected to 25°C and conductance of a sample at 25°C measured on an accurate surface bridge. The results of the corrected logs compared to a sample check generally showed a good correlation to within ±150 micromhos.

2.3.3.3. Sampling

A 1000 ml sample was collected from a short depth below the water level inside the casing. This sample would be representative of the water last pumped. Some deterioration in quality may have occurred in the subsequent static period but the main effect is likely to be a precipitation of supersaturated carbonate and, if any contamination should have occurred, reduction of sulphate. Samples frequently contained traces of oil. Shortly after collection, samples were coarse-filtered through fibre-glass millepore pre-filters prior to bottling.

2.3.3.4. Gamma Ray Logs

The majority were run in wells at or in the general vicinity of a proposed test drilling site. The purpose of these logs was to confirm the general suitability of a site for test drilling; and to determine accurately the thickness and vertical distribution of clay layers within the aquifer. Varying time constants and logging speeds were experimented with in order to obtain the optimum conditions for the particular requirements in mind since clay layers of a few feet in thickness can have considerable effects on a short duration pump test.

Gamma-ray logs were also run in a number of wells in the Augila field area and in Concession 108 in the vicinity of the P-M.M. outcrop boundary. In the former locality, the studies were concerned with a possible correlation of lithological changes with the very rapid changes in water quality which occur there. In concession 108 the logs were concerned particularly with obtaining information on the marginal horizons within the P. M. M. and older formations.

2. 3. 4. Test Drilling and Aquifer Testing

2. 3. 4. 1. Location of Test Drilling Sites

Test drilling was mainly concentrated in the lobe of good quality water occurring within the Post-Middle Miocene aquifer. Initial production sites were selected on the basis of the optimum combination of terrain (for irrigation), hydrological and geological factors. Due to a change in planning emphasis, some modifications were made in site selection criteria in order to obtain a more regional appraisal of resources. Basically the Exploration/Production wells were sited in the main areas of potential development and temporary Exploration wells in marginal zones. Both types of wells had associated observation wells/piezometers so that aquifer testing could be carried out. In two cases, the Exploration well drilled was used as an observation well and test pumping was carried out using an existing water well. A list of all sites is given below. At exploration sites, only one well was drilled. Numbers of observation wells drilled at Exploration/Production well sites are also noted.

Exploration/ Production Well Sites	Location	Numbers of observation wells drilled
JA	S1-103	1
JB	P1-103	2
JC	J1-103	1
JD	M1-12	2
JE	F1-103	2
JF	Q1-103	1

Exploration Well Sites	Location
(1)	KK1-12
(2)	F1-97
(3)	A1-LP5C
(4)	C1-95
(5)	A1-LP3C

2. 3. 4. 2. Design of Test Wells

The designs of test wells according to the specifications of the original drilling contact are shown in Text Figures 1, 2 and 3, and for a detailed explanation this document should be referred to. Modifications to the designs were incorporated in the course of the drilling programme and these modifications will be discussed below.

a. Exploration/Production Wells

Screens of 8-inch diameter were utilised. It had been originally intended to use screens composed of fibre glass but because of the fine-grain size of the aquifer sands and the relatively wide slots (2 mm) of the available screen, alternative screen types had to be used. Of the 6 E/P wells, three were completed with 20/40 slot wire-wrapped screen and graded gravel pack and three with slotted rubber-coated steel screen with a surrounding pre-pack uniform gravel filter. The 16 inch well casing was emplaced from 80 to 100 feet below the water table. This depth range was in effect a compromise setting. From the point of view of the longer-term available drawdown, a deeper setting may have been advisable. But as the main purpose of the drilling was for aquifer testing it was desirable that a major portion of the aquifer should be screened in order to ensure boundary conditions suitable for the analysis of pump tests of short duration. A modification to the original design introduced for the third and subsequent wells was to extend the cement grouting to the entire length of the 16" casing. The purpose of this change was to inhibit corrosion.

b. Observation/Piezometers (Single Type)

This type (Text Figure 2) was designed for initial exploration throughout the aquifer to determine lithology and water quality variations and to be completed so as to be suitable for use as an observation well during a pumping test. Water quality variations with depth cannot readily be obtained in an aquifer of unconsolidated material during drilling by rotary rig, and it was therefore planned to run slotted casing (alternate blank and slotted joints) throughout the total thickness of the aquifer so that quality variations could be subsequently determined by conductivity logging and sampling. It is known from measurements in water wells in the Sarir field area (Wright, 1969), which are completed in the same aquifer, that considerable quality variations with depth do occur. Since it was also planned to space the observation well far enough away from the production well to result in effectively horizontal flow patterns, the observed head changes in the well would be expected to be suitable for analysis. However, it was found during the first pumping test at JB, that in consequence of high-level clay layers above the screened section, the aquifer behaved during the test in leaky artesian fashion and, from observations in the high-level screen in a dual observation well at the same site (JB-02), no drawdown occurred at the water table during the five days duration of pumping. The drawdowns in the single, fully open and penetrative observation well were therefore compounded of the drawdowns of the confined 'leaky' aquifer section, modified by intercommunication through the slotted casing with the unconfined aquifer section above. No simple correction for such effects is feasible and the observation well in these circumstances is rendered virtually valueless. Subsequently observation wells completed were either of dual type or if single, were completed with access at the levels of the screened interval only of the pumping well. It is generally considered in the literature that a few feet of screen opposite the centre of the aquifer is sufficient. There are some possible disadvantages in this arrangement for a thick multiple aquifer which may result from the effects of localised poor development, poor screen setting or even vertical flow components within the main pumped well screen interval. It is considered advisable therefore to have observation wells open at a few selected intervals across the main screened section of the aquifer. As a general rule, some 10% is regarded as a minimum. Thus if a 300 ft section is screened some 30 feet in 3 or 4 spaced intervals would be provided. The resultant drawdowns are integrated values, which if the desired condition of horizontal flow is met would be identical at all four levels. But if this condition is not operative, there would in any case be insufficient numbers of piezometers available to monitor the differential changes. In these circumstances, it is considered better to obtain an average head value than a localised one which could provide very misleading results. Information on water quality variations with depth can be obtained from measurements in both single and dual observation wells and from the pumping well, both during the period of the pump test and during static conditions by conductance logging in the screened interval.

c. Dual Observation Wells/Piezometers

There were no major drawbacks to the basic design of this well other than the narrow diameter of the individual piezometers. Three and half inch tubing is too small for a float operated recorder and the pressure transducer systems were subject to erratic behaviour. In the later wells of this type 5 inch casing was used for one of the piezometers which did permit the use of float operated recorders. It would be advantageous in this respect to use 5 inch casing to a short depth below the water table for both piezometers. The only disadvantage in the proposal is the larger hole which is required with increased difficulties in demudding. It should be noted that an apparent leaky artesian condition can develop in a thick unconfined aquifer in consequence of vertical flow from the water table down to the screened intake. The initial purpose of the dual well was to observe head changes in the vertical section, which may occur even within a homogeneous water table aquifer. In these circumstances open hole intercommunication will mask these effects, and an effective collapse of the formation around the casing is therefore desirable. The use of a biologically degradable mud has advantages in this respect since a bentonite mudcake outside a blank section may well retain open hole conditions for some time after drilling with consequent ready intercommunication between different levels. If no convenient clay layer exists at which to set the cement plug, the latter of itself will not be a complete barrier.

Dual observation wells were subsequently used to determine head changes in the upper aquifer above the leaky artesian layer.

The length of the short piezometer is mainly conditioned by the requirement of the screen setting, but an additional factor had to be considered in development. Since airlift pumping was to be used to develop the wells, in order to obtain adequate submergence it was sometimes necessary to extend a blank section below the screen.

d. Screens in Observation Wells/Piezometers

On account of the frequent fine-grain size of the aquifer sands in the Phase 1 Area, torch slotted screens used alone proved unsuccessful. Not only were large volumes of sand brought in from the formation during development pumping, but continued to enter during subsequent natural flow conditions. In the case of JA-01A, the entire well was rendered useless due to sanding up. The following procedures were subsequently utilised to counteract this effect:

1. Emplacement of gravel pack/formation stabiliser around the slotted casing.

2. The use of a wire-wrapped screen with a fine slot (in this case .008 inches), as a substitute for torch slotted casing.

3. By wrapping torch-slotted casing with a fine wire mesh. The mesh used had an aperture size of ten thousandths of an inch and was double wrapped at an angle in order to increase strength and to reduce still further the aperture size. The annulus outside the mesh-wrapped screen was sometimes filled with formation stabiliser, particularly if a cement plug was to be installed at a higher level.

The wire-wrapped screen has considerable advantages over the other types in ease of emplacement and development and provided that the lengths used are not considerable, the cost difference is not great.

2.3.4.3. Drilling Procedures

It was intended to drill the first observation well at each site by cable tool rig in order to obtain good lithological samples and information whilst drilling of water quality changes. In the event, the method had to be discontinued after abandoning two holes, JA-01 and JC-01, due to difficulties consequent upon the fine-grain size and incoherence of the aquifer sands. All completed wells have been drilled by mudflush rotary rig. Reverse rotary was also considered but the rig did not become available during the Phase 1 drilling. The method may be used in Phase 2.

Drilling muds which have been used include normal bentonite and a biologically degradable mud known as Revert. The latter has the advantage of reverting to a fluid of the viscosity of water. The process can be delayed by the use of various additives. Revert was initially used for all observation wells and for the screened section of production wells. During the summer season, its use was temporarily discontinued owing to the high air temperatures causing premature reversion of viscosity. A number of wells were subsequently drilled using a bentonite mud containing Benex and demudding with a polyphosphate solution. Despite care in mud control, extended periods of development were required for all wells drilled with this mud and, in the case of JA-P, satisfactory demudding was never attained despite prolonged development including acidising.

2.3.4.4. Verticality

During drilling the verticality of the hole was measured every 60 ft approximately using a TOTCO tool run inside the drill pipe. In the majority of measurements, deviations did not exceed 1/3 of a degree.

Verticality in production wells is most critical in the upper section in which the 16 inch casing is emplaced. It is less critical in the screened section and if the drilling surveys are satisfactory and the screen is emplaced smoothly, there seems little purpose in running a screen survey. In the case of wide diameter (6.5/8 or 5 inch) observations wells in which a water level recorder is to be used, the verticality is critical to depths below the water level within the likely range of drawdowns during a pumping test.

The contract called for deviation of less than 20 minutes from the vertical for any section of the production well casing and for the larger-diameter observation wells to a moderate depth below the water table. The method of survey made use of a plummet, of a size slightly smaller than the casing, suspended at various depths with deviations measured of the suspended cable from the ground-level centre point of the well casing. The deviation of the centre of the well at the appropriate depth can be thereby calculated and also the direction of deviation. The method has certain disadvantages. When the deviation exceeds the diameter of the casing, the cable will be in contact with the casing and no further measurements are valid. Contact can be confirmed by noting the potential drop (electrical) between the casing at the surface and the cable. Although some conductance of electricity occurs through water, the effect when direct contact is made with the metal casing is considerably larger. A second difficulty in the application of this technique is that with a given combination of depth, casing size and deviation, the limit of measurement as explained above can be attained whilst still within the contractual limits. A different technique would be desirable, possibly employing some form of TOTCO device.

2.3.4.5. Lithological Sampling

Representative lithological samples are of great importance. The samples are required in order to make detailed sieve analyses to assist in the optimum setting of a screen and to determine the most appropriate combination of screen slot size and gravel pack design. The samples are also required in order to develop a correlation with permeabilities and porosities determined by subsequent aquifer testing and log analysis. The results can then be applied to extrapolate not only to the section of an aquifer not tested directly e.g. the unscreened sections of a multi-aquifer system but also to sites in which a single exploration borehole is drilled. The advantages of obtaining a successful correlation are obvious.

Various methods of sampling were utilised in the early stages of the test drilling programme. The final method arrived at has the following procedure:

1. Measurement of the mud circulation rate based on the strokes per minute of the mud pump and an appropriate calculation based on stroke length and pump liner size.

2. Calculation of the annular velocity and therefore the appropriate delay time for cuttings to reach the surface. Graphs were prepared for various combinations of sizes of drill collars and drill pipes so that the delay time could be read off against the appropriate depth and r.p.m. of the mud pump.

3. The samples are collected over a known 10 ft interval in accordance with the rate of penetration (geolograph) record and with due allowance for the appropriate delay time. Accurate geolograph readings are essential and the latter should be checked and if necessary corrected against every pipe tally.

4. A sampling offtake (3/8 inch bore) is inset at a downward acute angle on the conductor casing.

5. The mud sample for the appropriate interval is collected into barrels. The barrels are only half filled with mud and the number required for any one 10 ft interval will depend on the drilling rate. The barrels are

filled up with water and allowed to stand for at least half an hour, after which the residual drilling water is decanted off. The barrels are again filled with water and the contents thoroughly stirred and allowed to stand for an appropriate length of time for all material of sand grade (> 75 microns approximately) to be deposited. This period of time was calculated on the basis of Stokes Law and is the order of a minute or so. The residual drilling fluid and silt etc., is decanted off and the process repeated until all drilling fluid and clay material is washed away. Where Revert is used, the blue colour of the drilling fluid makes identification easy. During sampling, it is essential of course that the sand content in the circulating mud should be kept to a minimum by use of desanders and in this case the content was generally maintained at less than 2%.

The method of sampling does not retain material of silt or clay grade in the formational cuttings, and if this material should occur dispersed in the formations, there is no means of accounting for its presence other than in a general way by gamma-ray response. Where clays occur in discrete horizons, their location is apparent from the strong gamma-ray response. It has been noted that in zones with a probably high clay content, the uniformity coefficient of the sand sample tends to be abnormal.

Coring has been attempted in a number of holes with little success. Successful attempts have been limited to a sequence with interbedded clays within the Post-Middle Miocene at C1-95 and in a section of slightly semented calcareous sandstones of Miocene age at A1-LP5C. A double core barrel has been used with a so-called soft formation core catcher but the tool is clearly incapable of taking core samples from the unconsolidated sands of the upper unit of the Post-Middle Miocene.

2.3.4.6. Geological Logs

A geological log of the test drilled sites was prepared on the basis of the following data:

1. Oil Company records for the associated oil exploration well.
2. Drillers log. To save time and cost, lithological sampling was limited to the saturated section below the water table. Information on the higher levels is based on occasional visual observations on cuttings.
3. Rate of penetration logs.
4. Geophysical logs. Other than those in oil company records, additional geophysical logs are generally limited to gamma-ray. A more detailed set of logs were obtained in two sites of particular interest - at C1-95 in which the aquifer occurs in the more variable sequence of the lower unit (Aklash Formation) of the Post-Middle Miocene; and at A1-LP5C where test drilling penetrated into the deeper Miocene formations. These logs were run by Schlumberger and included microlog-microlaterolog, formation density and side-wall neutron logs. All the logs are primarily porosity logs and the purpose in running them was to obtain values to compare with direct measurements of porosity on core samples. A point of particular interest in the microlog-microlaterolog combination should be noted. At C1-95, the log was run in a hole with bentonite mud whereas at A1-LP5C, the hole was filled with Revert. In the former case, the log gave an appropriate positive separation in the permeable sand sections, whereas in the latter the relationship was reversed. No satisfactory explanation of this anomaly has been forthcoming. Revert mud is abnormally resistive but not to anything like the extent to cause the observed reversal separations. It would seem to indicate however that it is not advisable to run this very useful log in a hole filled with Revert mud.

2.3.4.7. Grain-size Distribution and Frequency Analysis

All samples from each 10 ft interval were dried, quartered and separated by sieves into size fractions. The sieve sizes and the grain size classification used in this report are listed in Table 1.

All measurements have been tabulated and are available on file. Grain size distribution graphs have been prepared for each sample by plotting the cumulative percentage retained by weight on the vertical scale against the logarithm of the sieve opening on the horizontal scale. The D_{50} size is used here to characterise the grain size. In the Appendices which accompany this report are listed the D_{50}, D_{90} and the uniformity coefficient (D_{40}/D_{90}) for each sample. The D_{90} size is such that 90% by weight is larger.

Size frequency curves have also been prepared for a selection of the samples as an attempt to determine the mode of deposition.

2.3.4.8. Well Completion

The P. M. M. aquifer consists of unconsolidated sands with a low uniformity coefficient [between 2 and 3], a median (D50) grain size between 200 and 550 microns and an effective (D90) grain size between 100 and 250 microns. For natural development a screen slot width of less than .010" would be required which is approaching the minimum size with can be readily manufactured and also the limit of hydraulic feasibility. An artificial filter (gravel pack) was therefore recommended to be used in all production wells [E/P and Exploration test wells].

Previous experience of the P. M. M. aquifer response to gravel pack completion is not well documented although a number of oil field water wells have been completed in this way. The most common failure has been excessive sand entry, followed in several instances by screen collapse, due presumably to shifting in the unconsolidated aquifer material with consequent fracture shearing of the screens. In designing the gravel packs for the test wells in this programme, particular attention has been paid to incorporating features which would prevent excessive sand movement.

a. Pack Operation

The purpose of a pack is to exclude all aquifer material from the well during eventual production, and to reduce to a minimum the hydraulic resistance to flow in the vicinity of the well. The main control in effective filtration is bridging of the sand grains whereby adequate fluid movement is permitted without sand transport. Bridging action is related to pore size and pore velocity.

Gravel packs are of two types, uniform and non-uniform, (or graded). In theory, the former would be composed of single sized particles but in practice the term is applied also to packs with a uniformity coefficient less than 2. The precise difference in operation between the two types of pack is not entirely clear and there are undoubtedly transitional features.

The uniform pack is most suitable for very uniform formations and its design is based on the grain and pore size which will retain most of the formation material. There is therefore a marked interface between the aquifer and pack and although some development in the former may occur by initial loss of fine material, this abrupt transition is thought to be maintained in subsequent operation. Movement of the aquifer into the pack is believed not to occur in a properly designed pack and there is some theoretical proof that this is so, although the precise critical limits of design are by no means certain. The advantages of the uniform pack are simplicity of design, ease of emplacement and high permeability. The main disadvantage is its sensitivity to changes in formation grain size which could result in either an unstable relation with consequent sand movement, or alternatively filter blocking. It is obvious that the mode of operation requires the pack to remain unchanged and the screen slot size should retain the entire pack.

The graded pack is intended to develop a smooth transition between aquifer and screen by progressive movement of aquifer material both into and through the pack until a stable configuration is developed with increasing grain size towards the well. This development results from a close conformity of the pack design to the basic aquifer grain size distribution. The graded pack is suitable for use with an aquifer of variable grain size. It has obvious advantages in a thick aquifer for which detailed information on formation characteristics is costly or difficult to obtain. Its main disadvantages include the lower permeability as compared with a uniform pack, and the difficulties of emplacement without segregation.

b. Aquifer Failure

This is manifested either by excessive sand movement or by filter blocking. Sand movement is related to pore velocity and the pack-aquifer ratio. Critical values of pore velocity are directly proportional to the particle diameters. The relation with the pack-aquifer ratio is more complex but it has been found that critical values exist above which the configuration becomes unstable and sand movement occurs. The correlation appears to lie in the mechanism of bridging whereby the larger sand grains interlock at the gravel interface with cumulative bridging of the smaller grains upon the larger. The explanation accounts for the common phenomenon of initial sand movement at changes of pumping rate which continues until a stable configuration is re-established. The explanation also accounts for the generally greater effectiveness of the graded pack in preventing sand movement as compared with the uniform pack.

A subsidiary influence on sand movement is cohesion which seems to increase the stability of finer-grained materials. Cohesion also increases sometimes with increasing hydraulic gradient and the feature is perhaps the result of compaction.

Filter blocking will occur if the gravel pack is of too fine a grade or badly graded in relation to the aquifer.

c. Pack Design (General)

Both uniform and graded packs have been used in the test Exploration/Production wells. The former have been of pre-pack design [Hagusta manufacture] and utilise a slotted steel screen with rubber coating. The latter have been emplaced around a wire-wrapped screen with slots varying between .020 and .040 inches. Formation details of aquifers and packs are shown in Table 2.

d. Uniform Pack

The only significant variable in the uniform pack is the pack-aquifer (P-A) ratio. It is generally referred to the D50 sizes as in Table 2. but can be used for any equivalent pair. P-A ratios must be low enough for a stable configuration (i.e. with respect to sand movement) to exist and as high as possible to obtain maximum permeability. Complete design data should therefore include entrance velocities based on production rates, screen length and open area, aquifer uniformity and size variations. In making empirical comparison of results, information on hydraulic gradients should be noted since this may relate the cohesion effects.

Kruse 1960, refers to investigations showing that filtering action is likely to be unstable if less than 15% of aquifer material is retained. This size limit cannot be connected directly with calculated gravel pore size since a precise relationship of bridging characteristics across an aquifer-pack interface has not yet been established. This distinction is made clear by the calculation below. Assuming that the porosity of the pre-packs used is 30% (exact data yet to be obtained from Hagusta), the pore sizes for a uniform pack of 950, 1500 and 2500 microns (median sizes of ranges used) would be 30% of the corresponding particle size. In Table 3 below, the calculated pore sizes are compared with the grain sizes passed and retained by the various packs used. [Latter figures supplied by manufacturer]. It should be noted that the optimum design specification for slot entrance velocity is 3 cm/sec which was not exceeded during the production tests.

A more precise correlation between actual pore velocity and grain sizes will be provided in the final report but the results do show that the grain sizes which are retained are considerably smaller than the pore sizes. Information on the aquifer relations has not been obtained from Hagusta but presumably this effect can be attributed to bridging.

Until precise information on bridging in relation to pack-aquifer (P-A) ratios is available, the latter must be determined using experimental observations. Kruse, 1960 recommends that a limiting P-A ratio of 9.5 should be used for uniform packs with uniform aquifers and 13.5 with non-uniform aquifers. The higher allowable P-A ratio for the latter accords with the theory of filtration. Pack permeability will increase with ratio size, assuming a stable configuration. Smith, 1954, recommends a P-A ratio of 4-5 based on observed well efficiencies in 20 wells and notes a reduction in efficiency for both lower and higher ratios with excessive sand production occurring above a ratio of 10. The result in relation to efficiencies between the P-A ratios of 6-9 is a little anomalous since it would be expected that head losses would be at a minimum for the maximum stable P-A ratio. [No distinction is made for variation in aquifer uniformity]. Schwarz, 1969, recommends a P-A ratio of 6 but uses a critical grain size in the aquifer which is multiplied by 6 to give the corresponding gravel size. In a uniform aquifer, the critical point is the D10 size; for a non-uniform aquifer with low velocity, it is the D40 size and with high velocity, the D90 size. These relations are empiral but based on theoretical considerations and can therefore be used as design constants to be tested experimentally.

Uniform pre-packs were used in JD, JE and JF (Table 3). The lengths of screen are comparable, and the design specifications of P-A ratio accord with Smith's and Schwarz's recommendations. No significant amounts of sand were produced in any of the three wells during the main pump tests and well efficiencies are fairly similar.

e. Graded Packs

Graded packs are normally designed to have the same uniformity coefficient as the aquifer in order to assist the development of a progressive stable transition between the pack and aquifer. The limiting P-A ratio according to Kruse is 17.5, or if a graded pack is to be used with a uniform aquifer, this should be reduced to 13.5. These ratios are higher than those recommended by other authorities such as Terzaghi (1948), the US Dept of Agriculture and the US Bureau of Reclamation in which the factor is between 5 and 8.

A graded pack with low uniformity coefficient comparable to the aquifer was utilised in JA-P JB-P and JC-P. (Table 2). The P-A ratios averaged between 7 and 9 with ranges between 7 and 12, thus approaching the lower limiting value of Kruse. In the latter two test wells, no significant sand entrance occurred during production. Excessive sand entrance did occur at JA-P but this was almost certainly the result of poor gravel emplacement with local bridging. The general results do tend to confirm the findings of Kruse. Well efficiency results are anomalous. The results of JB and JC only can be utilised and in one case (JB-P) it exceeds that of the pre-packed wells and in the other (JC-P), it is considerably less.

f. Pack Emplacement and Thickness

A gravel pack should be thick enough to ensure that the screen is fully surrounded. Too wide a pack makes demudding and completion difficult. It has been shown that a width of 5 grain diameters will create an effective bridge, but a general recommendation is between 3 and 6 inches. The former size was used in the Phase 1 test wells. Roscoe-Moss (verbal communication) recommend a very wide gravel pack associated with a wide screen aperture and powerful development techniques in which large quantities of both gravel and sand are drawn through the screen into the well until a stable configuration is developed. The value of this combination seems doubtful, and since a larger hole is required, the drilling costs are increased.

Emplacement of the graded packs in two of the three test wells was done through a pipe clamped on top of the screen with openings at the base, the movement of gravel being assisted by an air line set at screen level. With this method, emplacement occurred without bridging or hole collapse. It had been intended to mix a selection of radioactive glass beads in with the gravel mix in order to check on segregation by a gamma-ray log but in the event this was not done. Size segregation was thought unlikely in view of the small diameter feed pipe and annulus. The varying levels of gravel in the annulus (tested by a feeler pipe) corresponded closely with the volumes of gravel used. In the case of JA-P, gravel emplacement was carried out through the annulus between the central pipe and the 16 inch casing and bridging occurred during emplacement. The method also had the disadvantage of a greater likelihood of size segregation occurring.

g. Screen Type

Screen types used in this programme have included torch-slotted steel casing or tubing in the temporary Exploration and observation wells, and wire-wrapped welded screen or rubber coated steel machine slotted screen in the Exploration/ Production wells.

Torch-slotted casing was used for reasons of convenience and cost but machine-slotted casing would have been preferable, had it been available, and would have cost little more. Torch-slotted casing is difficult to swab unless the internal 'slag' is removed. It was also noted that the casing joints were inclined to warp in the process of slotting. An open area of 5% minimum was requested with slots between 1/8" and 3/16" wide, one foot in length and arranged en echelon. To inhibit warping, alternate 5 feet lengths were left blank.

h. Screen Length, Diameter and Slot Size

The minimum screen diameter is that size which can carry the maximum well discharge without excessive friction loss. Assuming a friction loss of less than one foot and a discharge of 1500 gallons per minute, eight inch diameter screen is adequate. Increasing screen diameter will improve specific capacity but the improvement is marginal unless the size increase is very large.

Screen length should relate to the amount of aquifer that is required to produce the desired discharge. For the test wells, it was desirable to screen the maximum section consistent with drawdown requirements in order to obtain optimum boundary conditions for aquifer testing and between 160 and 170 feet of aquifer was screened. It was intended to run flow velocity logs to assist design criteria for future production wells but owing to equipment difficulties, only one well was successfully tested. In JE-P, it was found that over 91% of the flow came from the lower 2/3 of the screened interval and on the basis of this information, it would seem theoretically possible to reduce the screen length by one third and still obtain almost the same specific capacity.

Two other aspects need also to be considered in relation to screen length, namely the effects of clay layers (i) in relation to aquifer response, i.e. whether unconfined or artesian and (ii) in relation to vertical flow components. Considering the latter case, a partial penetrating well with shorter screen length measured towards the base of the aquifer could prove adequate but may significantly reduce efficiency due to intermediate clay layers inhibiting vertical flow upwards from the section below the screen. On this account, it would seem unwise to limit screen length downwards without adequate depth velocity tests in initial production wells. There are theoretical methods of calculating minimum screen lengths (Peterson et al, 1955) but they require detailed information on three dimensional permeability which is difficult to obtain.

It is customary to case out the upper section of a water table aquifer to below the pump setting in order to avoid mechanical damage and chemical corrosion of the screen. Aquifer testing in this programme has shown that in consequence of high level clay layers, the aquifer responds under these conditions as a leaky artesian aquifer and not a water-table aquifer. Drawdowns are consequently higher. The effect is being studied and will be discussed in the final report.

Consideration is being given to the possible improvements in long-term specific capacity by extending the well screen upwards above the pump setting. It would be necessary to incorporate special design modifications to offset the potential ill-effects mentioned above.

i. Screen Slot Size and Slot Area

Since it is desired to retain the emplaced gravel pack as much as possible, the screen slot size should be fairly small. A generally recommended size is the D90 of the pack and with a P-A ratio average of 8, a slot of between 0.020 and 0.040 inches would be required.

Total slot area should be as high as possible consistent with mechanical strength in order to reduce entrance velocities to a minimum. A low entrance velocity will keep pore velocities in the immediate vicinity also low and will inhibit both encrustation and corrosion. The optimum design limit for slot entrance velocity commonly quoted is 0.1 feet per second. With the length of screen recommended (100/150 feet), and even allowing for appreciable plugging, an open area of 10% would be adequate to maintain entrance velocities below this level.

j. Screens Material and Type

Screens should preferably be composed of such non-corrosive material as stainless steel or fibre glass. The use of fibre glass is hindered by the small slot size required, and experimental studies are recommended to determine whether a gravel pack of the recommended grading could be retained by the slot size it is mechanically and hydraulically feasible to use in this material.

k. Gravel Material

Gravel should be composed of clean, well-rounded, preferably siliceous material. Care must be taken not to include water-soluble material such as limestone, gypsum or anhydrite or such contaminants as shale, clays etc which would impair bridging capacity.

l. Recommendations

In view of the thickness, uniformity and grain size of the P. M. M. aquifer, a gravel pack is recommended as opposed to natural development. The pack should be of the order of three inches thick and composed of well-rounded stable siliceous material. For ease of emplacement without segregation problems, a uniform pack is to be preferred although a graded pack with a low uniformity coefficient about 3 could be considered if sand pumping should prove excessive with a uniform pack. Average P-A ratio for the uniform pack should be between 4-6 and for the graded between 7-9.

The screen slot size should retain 90% of the pack material and will probably range between .020 and .050 inches. Wire wrapped screen is undoubtedly the type which is most hydraulically suitable. If fibre glass screen is required for cost reasons, slot size should be kept as near as possible to the limits quoted and it should be recognised that sand pumping may result if the size is too great so that the pack is disrupted.

Production wells should be drilled to the basal clay layer of the P. M. M. aquifer which in the central Phase 1 Area is around 500 feet below ground level. Well screens of 8 inches diameter are adequate for the desired production rate (1250-1500 US galls/min), and if normal practice is adhered to, the lower section of the aquifer only will be screened. For increased available drawdown, the casing could be increased to around 150 feet below the water table which in the proposed well field area would give a screen length of 100 feet. Alternatively, it may be considered worthwhile to experiment with a test well with screen level increased upwards above the pump setting in order to obtain horizontal flow with water table conditions and in consequence increased specific capacity and reduced drawdowns. The upper screen would require to be large enough to contain the pump bowl but the lower section could reduce to eight inches.

A slotted screen with pre-pack filter has been used successfully in the test wells and its use could be recommended for production wells. It would probably compare in overall price with a slotted fibre glass screen with emplaced pack. It has been suggested that removal of encrustation is difficult in a fixed gravel pack and some assurances from the manufacturer would be desirable on that issue if such screens are proposed for use.

2. 3. 4. 9. Aquifer Testing

a. Purpose

To obtain information on the hydraulic boundary conditions which operate during artificial production; to determine the aquifer characteristics, transmissibility and storage coefficient; to assist in the formulation of design criteria for future production wells.

b. Design

Aquifer testing was based on the analysis of step-drawdown development pumping and constant rate pumping tests using production wells with two or more observation wells.

Production wells were of two types:

(i) Exploration/Production wells fitted with a turbine test pump producing during constant rate test generally between 1000 - 1250 US galls/min.

(ii) Exploration wells of small diameter producing by air lift at rates between 150 and 200 US galls/min.

The E/P wells were sited in the optimum area of potential development and the Exploration wells in outlying marginal locations. Observation wells included recently drilled wells of single or dual completion type plus any existing wells which could be used for this purpose. All test sites were located near groups of existing wells, which usually occur in groups of two spaced 20 to 30 metres apart and completed with 6 and 5/8 inch casing and a short screen near the base. Screens are commonly of the order of 7-10 metres in length and composed either of manufactured commercial types or torch-slotted casing.

It was assumed initially that the aquifer would behave in unconfined fashion. Exploration Production wells were required to conform to potential production well standards and were therefore cased to a sufficient depth (c. 30 m) below the water table to allow for pumping drawdowns. Screens extended to the base of the aquifer (c. 50/55 m below casing).

Initial planning located a dual observation well relatively close (c. 60 m) to an E/P well in order to assess the significance of vertical flow components. Other observation wells were sited at distances where it was thought horizontal flow patterns would prevail. These further observation wells were sited in line with the E/P well and generally at right angles to the line joining the E/P and dual observation well. The purpose in this site plan was to obtain indications of varying aquifer characteristics in different directions as well as to provide suitable data for distance-drawdown analysis. Because of the uncertainty of aquifer response, a site evaluation by response prediction was not feasible for the initial test wells. For the later tests in which information on the operating boundary conditions was available (i. e. leaky artesian with limited responding section), a generalised response prediction was utilised in order to select observation well locations which would permit an adequate range of time-drawdown measurements for data analysis.

Site plans for Exploration well test sites were related to the lower production rates by air lift and the spacing of the existing wells. No additional observation wells were drilled at such sites and site selection was influenced by the suitability of the existing wells for aquifer testing. The most significant control was the extent and position of the screens in relation to the local responding section of the aquifer.

c. Pre-Test Requirements

All existing wells were cleaned out, if possible, to the perforated interval and 'slug' tested to determine the effectiveness of hydraulic response. The latter test was done in all newly drilled observation wells as a check on hydraulic response and also for dual-type wells, to check on the effectiveness of the cement plug between the two 'strings'.

After cleaning, water levels were allowed to returnto equilibrium and the barometric responses observed to obtain drawdown correction factors. Prior to carrying out the main constant rate pump test, a period of standstill - 24 hours was generally sufficient - was allowed for full equilibrium to be established.

d. General Test Procedure

The pumping tests had durations of three days in the case of Exploration well tests and between 5-10 days for E/P wells. Drawdown and recovery measurements were carried out manually for the first 100 minutes of the cycle and thereafter by autographic recorder or by periodic observations of sufficient frequency for the data plot.

e. Methods

The methods of measurement and the accuracy limits are listed below:

i. Pumping well discharge

1. Tank with plan dimensions of 11.5 by 2.45 metres [$\pm$ 1.5%]. The tank was used to calibrate all other measuring devices. The tank was sited approximately 300 metres from the well head and a channel was dug beyond to lead discharge down any natural gradient which existed. The discharge main which lead from the well head to the tank was eight inches in diameter with the orifice plate and up to three pipe flow meters set in line. A bypass manifold was fitted around the flow meters for use during development pumping as the meters were sensitive to sand content. The discharge main entered the tank from above in order to maintain sufficient back pressure under low flows to keep the main full.

Tank measurements only or latterly combined with weir measurements plate were used for measuring discharge during airlift production tests.

Discharge rates were commonly maintained to within 2% except for reasons of pump failure (engine or compressor) or in the two cases - JA and JE - where the drawdowns reached the limiting level of the pump suction. Maintenance of production rate was found to be more effective by engine than by valve adjustment.

2. Five inch orifice plate and mercury manometer [± 6-10%]. The accuracy of this could have been improved by increasing the upstream straight line section from 30 to 40 feet. The orifice plate was mainly used as a general check on the maintenance of discharge rate.

3. Rectangular weir plate on tank [± 2.5% on calm days]. Baffles and a stilling pipe were used but accuracy still decreased markedly in windy weather.

4. Pipe flow meters. Three were set in line and the range in readings was of the order of ± 2% from the mean. For the later tests the meters were inoperative due to mechanical failure.

5. Depth flow velocity meter [E/P wells only]. Due to difficulties of emplacement and mechanical trouble this meter was used successfully in only one well (JE-P) and the result showed close correlation within a small percentage with the measured surface discharge. An improved design with some form of adjustable caliper device permitting centralised setting in use and subsequent withdrawal with the pump in place would be desirable.

ii. Synchronous time: accurate stop watches comparable to within one second.

iii. Pumping well water levels: electric probe [± 0.3 metres]. The low accuracy can be ascribed to surging, oil on water surface or stretching of cable in consequence of periodic trapping against pump column collars. For later tests an access tube was run in along with the pump column.

iv. Depth to water levels in observation wells:

1. Electric probe [± 0.03 m]

2. Water level float operated recorder. A similar order of accuracy can be attained to the electric probe but errors did occur due mainly to float sticking in the casing, particularly in the small diameter $3\frac{1}{2}$ inch tubing.

3. Pressure transducer and chart recorder. [± .05 m according to setting]. This equipment proved unsatisfactory during the Phase 1 test series.

v. Elevation of measuring points: by theodolite.

vi. Well depth:

1. By plumb bob and calibrated cable [± 0.05 m].

2. By plumb bob with digital readout [± .5 m].

vii. Levels of screen intervals: by contractors pipe tally.

viii. Site plan: tape and theodolite.

f. Data Analysis

i. Pumping well. Level changes were used to obtain specific capacity ratios only. Recovery plots could not be made because, for mechanical reasons, no foot valve was fitted to the test pump column.

ii. Observation wells. Drawdown and recovery measurements were plotted against time on log-log and semi-log paper. The form of the plots suggested leaky artesian conditions, and since drawdowns in the upper aquifer levels were either of small or negligible proportions, the results were analysed according to that theory. The thickness used for permeability calculations was related to the adjacent clay layers above and below the screened interval. Distance-drawdown plots were made for time periods before departure from the Theis curve. Semi-log plots for time-drawdown were considered in relation to the time required for the log approximation to become valid and to the effects of leakage. On both accounts, transmissibility values would tend to be exaggerated and the log-log analysis was therefore considered to provide more accurate results.

2.3.4.10. Hydrogeochemistry

a. Sampling

Samples were taken for specific electrical conductance (SEC) measurements throughout the main pumping tests as a general check on quality changes. Samples were collected at the beginning, middle and end of each pumping test and retained for subsequent chemical analysis. Two samples were collected at each time, the first, a 500 ml sample filtered through 0.45 m Millipore filters and acidified with high purity HCl and the second an unacidified sample for field bicarbonate and subsequent laboratory chloride analysis. An untreated sample (30 ml) was collected at the end of the test for stable isotope analysis and 3 x 60 litres of water were collected and sealed in large drums to await processing on site for Carbon - 14 analysis. At certain sites samples were collected and sealed in (500 ml) glass bottles for tritium analysis.

b. Field Chemical Analysis

pH : Analysis at the well head using glass drums pH electrode (Electronic Instruments Ltd.,) and Orion specific ion metre, taking particular care with temperature equilibration (Barnes 1961).

HCO_3 : Analysis in the site laboratory on a tightly stoppered samply by potentiometric titration using 0.01N H_2SO_4 and pH equipment as above to follow the pH change. End point determined as maximum inflection in titration curve.

CH : Analysis on pumped discharge using a specially designed anaerobic cell and a dual platinum - reference electrode (Orion). The millivolt change was monitored until a stable reading was obtained.

c. Corrosion

Corrosion rates were determined using a Corrater (Magna Corp,) with a variety of standard and special probe tips. The individual probes were inserted in the anaerobic cell and readings taken at switched polarities once stability was obtained.

d. Laboratory Reports

All chemical analysis were carried out at the Hydrogeological Dept., Institute of Geological Sciences and the methods used were as follows:

Chloride : Titration with Ag NO_3 using an Orion solid state silver/silver sulphide specific ion electrode to detect the end point. Grans' plot paper was used to plot the results.

Sulphate : Titration with barium perchlorate using thorin as indicator.

Nitrate : Direct analysis using Orion nitrate specific ion electrode and interfering ions.

Sodium : Atomic absorption spectrophotometry (AAS) using potassium as releasing agent and air-acetylene flame.

Potassium : AAS using sodium as a releasing agent and air-acetylene flame.

Calcium : AAS direct using nitrous oxide - acetylene flame.

Magnesium : AAS direct using nitrous oxide - acetylene flame.

Strontium : Using potassium buffer and air-acetylene flame with lanthanum-potassium buffer.

Fluoride : Direct with Orion fluoride solid state specific ion electrode and buffer to adjust for ionic strength and to liberate complex fluoride ions.

Boron : Colorimetric using curcumin as indicator.

Total Iron : AAS direct at high concentrations.

Manganese : AAS direct at high concentrations.

Cadmium, Cobalt, Copper, Lead, Nickel, Zinc, (Iron) : Solvent extraction of mixed metals using acetylacetone, 8-hydroxy quinoline and olithiozone as chelating agents and ethyl propionate as solvent. Analysis of individual metals separately using AAS with air-acetylene flame.

Phosphate : Colorimetric determination using ammonium molybdate, ascorbic acid and antimony potassium tartrate.

Lithium : Direct by AAS

Bromide : Colorimetric determination based on oxidation of iodine to 10_3 by K Mn04 and the effect of bromine on the rate of reaction.

Stable isotope determinations were carried out by the IGS (Stable Isotope Unit), tritium analysis by the Atomic Energy Research Establishment, Herwell, and Carbon - 14 analysis were undertaken by the Scottish Research Reactor Centre, East Kilbride.

e. Carbon - 14 Processing

At the beginning of field studies Carbon - 14 samples were obtained using a modification of the method of Cresby and Chatters (1965) but this was eventually rejected except for groundwater less than 1000 mg/1 dissolved solids. Concentration of subsequent samples were carried out by recycling in a closed system on site from the 60 litre vessels into traps of 5N Na0H. The system was purged with N_2 which acted as carrier gas and cycling was effected using a peristaltic pump. The Na0H concentrate was then sealed for shipment to UK.

2.4. GEOLOGY

2.4.1. General

Much of central Cyrenaica is covered by a vast spread of surface sands and gravels which is bounded to the north and north-west by outcrops of Miocene rocks, mainly limestones, and to the south-east by the Mesozoic and Palaeozoic outcrops of the Jebel Dalma (Map Figure 4). The Phase 1 Area lies in the north-west corner of this region overlain by surface unconsolidated sediments and extends west into the Miocene outcrop where the beds dip gently to the north-east.

The Phase 1 Area occurs within the structural unit known as the Sirte Embayment (Conant and Goudarzi, 1967, p. 724, fig. 2). This is a heterogeneous structural feature which developed initially in upper Cretaceous times on the site of an eroded structural 'high'. Subsequent subsidence and extensive marine transgressions were associated with block faulting. The late Mesozoic and early Tertiary deposits were controlled by tectonic influences with the development of thick sequences of bituminous shales in the sinking grabens and thinner, more variable successions including evaporites, in the horst blocks. By Eocene times a marine transgression had extended from the main basin south-westward into a deep embayment reaching the Tibesti area and possibly beyond. Subsequent regression commenced in the Oligocene and resulted in the northwards spread of clastics. Regression continued into the Miocene and culminated in the complete withdrawal of the sea together with the development of widespread and deep terrestrial erosion patterns, probably in late Miocene times (Barr and Walker, in press).

Marine transgression, probably in early Pliocene times, resulted in the deposition of marine sediments some little distance south of the present shoreline of the Gulf of Sirte. Further south, continental sedimentation commenced giving rise to thick sands with occasional interbedded clays, and has probably continued intermittently to the present day.

2.4.2. Regional Setting

The phase 1 Area lies on the north-west margin of the region covered by previous IGS hydrogeological investigations (Wright and Edmunds, 1969) and Map Figures 4, 5 and 6 are from this earlier report. Map Figure 5 shows a number of geological cross-sections (lines of sections shown Map Figure 4) and Map Figure 6 a lithofacies map of the post-Eocene formations in Central Cyrenaica. The post-Eocene formations thicken towards a central north-south trending axis with Oligocene and Miocene rocks outcropping in the west and dipping eastwards below younger formations in the centre. It should be noted in this context that the 'upper series of unconsolidated sands' in Area IV, [Map Figure 5] includes sands of Oligocene and Miocene age, as well as Plio-Pleistocene to Recent. This is apparent from the surface geological map.

2.4.3. Stratigraphy of the Post-Eocene Formations

Generally, throughout the Sirte Embayment the highest horizon to be regionally correlated in oil company well logs is the top of the Upper Eocene, (Augila Formation). Hence in the earlier regional hydrogeological investigation (Wright and Edmunds, 1969), lithological variation and lithofacies definitions were formulated for this relatively thick Post-Eocene interval.

In certain concessions, the operating companies have, however, distinguished higher horizons. Thus a conformable passage from Upper Eocene into Oligocene sediments is often recognised, but only very rarely is an upper boundary drawn between these and the overlying Lower and Middle Miocene. The uppermost boundary recognised is that between the Lower and Middle Miocene (Marada Formation), and the overlying, poorly consolidated sands, variously described as being of Plio-Pleistocene, Pleistocene or Quaternary age, but for want of specific palaeontologic data best referred to as being simply Post-Middle-Miocene in age. The number of boreholes in which this boundary has been identified by the oil companies is, however, small.

In the Phase 1 Area, attention has been concentrated on the upper approximately 1000 feet (305 m) of the sequence, and in particular on the definition of the boundary between the Post-Middle Miocene and the underlying Lower and Middle Miocene. The detailed studies of the oil company records outlined above have shown that this boundary can be picked in all boreholes in the eastern two-thirds of the Area.

In addition the Phase 1 Area studies have shown that the Post-Middle Miocene can be subdivided into a lower unit of generally clayey sands and poorly consolidated sandstones, clays, and occasional limestones, and an upper unit consisting of dominantly sands with medium fine and coarse sand and occasional thin clays.

In an earlier account of the stratigraphy of the Phase 1 Area (Benfield 1972) the two subdivisions of the Post-Middle Miocene were referred to informally as the Lower Unit and the Upper Sands respectively. These names have also been used in the Completion Report Appendices which accompany this Report. However, against the background of the recent introduction of a formal stratigraphic nomenclature for the subsurface rock units of the Sirte Basin (Barr and Weeger, 1972), it now seems advisable to name these units in accordance with the Code of Stratigraphic Nomenclature (American Commission on Stratigraphic Nomenclature 1961). The Lower Unit has, therefore, been named the Aklash Formation, the name being taken from that of the wadi running in a northerly direction through the south of Concession 95 where the Formation is most thickly developed. The Upper Sands will be referred to as the Calanscio Formation, the name being derived from the Calanscio Series which extends over the two-thirds of the Phase 1 Area. Formal definition of those formations and full details of type sections will be included in the Final Report.

Table 4 presents a summary of the stratigraphic succession of the Phase 1 Area.

2.4.3.1. Oligocene

Oligocene sediments are present in the whole of the Phase 1 Area but almost everywhere are covered by varying thicknesses of Lower and Middle Miocene and later sediments. In a small region in the southwest of the Area, around TTT1-59 it seems probable however that Oligocene sediments constitute solid bedrock below the recent Waha dune sands.

No detailed appraisal of the data contained in oil company records has been made for the Oligocene formations. However, a brief assessment of the nature and thickness of the sediments based on previous IGS investigations and other published information is included here for possible future reference.

Lithological and general thickness variations are indicated in Map Figure 5, cross section I-I which transects the southern Phase 1 Area. The Oligocene consists predominantly of sandstone with shale interbeds, outcropping below and to the west of the Miocene scarp (around B1-59) and dipping eastward under Miocene rocks. In the north of the Phase 1 Area, the Oligocene increases in thickness and shale content (Fig. 5, cross-section IV-IV).

In the south, south-east and east of the Phase 1 Area, Barr and Weeger (1972) report that the Oligocene comprises two formations, the Arida Formation below and the Diba Formation above. The Arida itself divides between a lower unit, comprising thick fine grained, glauconitic sandstones with occasional thin laminated shale interbeds, and an upper unit consisting of soft glauconitic shale. In the type section, located in Oasis E3-59 Well, the lower unit totals 330 ft in thickness and the upper 65 ft. The overlying Diba Formation is made up of an alternating sequence of thick, fine to coarse grained, commonly glauconitic sandstones and thin shales. Occasional sandy limestones may occur towards the top of the formation. At its type section, also E3-59, the formation is 594 ft thick and the whole Oligocene section totals 989 ft.

2.4.3.2. Lower and Middle Miocene

a. General

The outcrop of Lower and Middle Miocene rocks which occupies the south-western third of the Phase 1 Area is continuous with those around Marada Oasis some 70 km further west. These rocks were first described by Desio (1935) and named by him the Marada Formation. Subsequently, Selley (1969, p. 423) restricted his use of the term to those sediments lying beneath a prominent marine limestone, commonly outcropping around the tops of the jebels of the Marada region, which he suggested might correlate with the Marmarica Formation of the Western Desert of Egypt. More recently, however, Barr and Weeger (1972) have indicated that the Marada Formation should include the whole of the Lower and Middle Miocene sequence of the south-west and south of the Sirte Basin and this usage is adopted here for the whole of the Phase 1 Area.

The thickness of the Marada Formation varies markedly. At outcrop, around the type locality, Barr and Weeger (1972) report a thickness of 490 ft (149 m). In the centre of the Phase 1 Area, the present studies indicate thicknesses of the order of 1000 ft (305 m), while Roberts (1970) suggests a thickness of approximately 1500 ft (457m) for the Amal Field area to the north-east.

The Marada Formation generally comprises mainly limestones and dolomites, commonly sandy, with interbedded clays grading to shales. Clay becomes the dominant lithology only in the far north-west of the Area. Sandstones, generally fine grained, but reaching coarse to very coarse in places, are less common but form a significant proportion of the succession to the south-west. Gypsum and/or anhydrite occur widely and are associated with both the clays and the carbonates. The evaporites may occur within the clays as discrete thin beds but are also found disseminated through both lithologies.

In comparison with the overlying Post-Middle Miocene, logs of the Lower and Middle Miocene show a number of points of contrast. Where the latter comprises a carbonate-clay sequence, differences in the resistivity and BHS logs are particularly well marked. However, even where the Lower and Middle Miocene presents a sandy facies, significant differences occur. There is an overall increase in gamma values and a general drop in resistivity, while the pattern of the BHS log shows a marked change reflecting the greater degree of consolidation. Such differences permit distinction between the two major parts of the succession even where the Aklash Formation is absent and the Calanscio Formation rests directly on the Marada Formation.

Evidence of the age of the beds derives principally from the presence of a marine fauna which includes foraminifera. These have been investigated by oil company palaeontologists who have classified the strata as Lower and Middle Miocene.

The dominance of marine limestones and clays indicates that the bulk of the sediments were deposited in a shallow shelf environment. The presence of evaporites suggests that conditions became lagoonal at times, while the sands were probably laid down in a variety of shoreline environments. The pattern of lithological variation over the area throws further light on the depositional environments and this is discussed below.

b. Areal Lithological Variation within the Upper 500 ft (152 m) of the Marada Formation

In the majority of well logs utilised in the Phase 1 Area neither the base of the Marada Formation nor any internal subdivisions are defined by the oil companies. Since insufficient time was available to undertake detailed correlation studies, investigations of the variation in lithology of the Formation within the Phase 1 Area were restricted to an arbitarily defined unit, the 500 ft (152 m) of strata immediately underlying the Post-Middle Miocene, to which standard lithofacies analysis techniques (Krumbein and Sloss, 1965) were applied. This unit was selected because the existing water wells in the outcrop area extend generally to this order of depth. Values for the total thicknesses of the primary lithologies and the corresponding isolith contours (Map Figures 1c, 2c and 3c) have been plotted using the IBM 1130 Computer of the IGS Computer Unit. The program utilised was the IBM 1130 Numerical Surface Techniques and Contour Mapping Program. It should be noted that, because of the way this Program operates, several zero contour lines may be plotted in areas where geologically it would be expected that the lithology under investigation would be completely absent. The distribution of total thicknesses of sand and sandstone within the upper 500 ft (152 m) of the Marada Formation (Map Figure 1c) shows that the Phase 1 Area may be divided into three north-west to south-east trending belts. The north-easterly belt is essentially sand-free. Within the central belt, values vary markedly but the isoliths define a major north-easterly directed lobe of increased sand content occupying the centre of the Phase 1 Area. The lobe appears to bifurcate, a northerly pointing branch situated over much of Concession 103 and a north-easterly branch lying to the north-west of Gialo Field. Maximum values are found in the south-westerly belt where total sand thicknesses reach 449 ft (137 m).

The overall pattern of the isoliths generally suggests the combined effect of a north-west to south-east longshore trend and a north-easterly directed sand input. Such a pattern compares well with that documented by Selley (1966, 1967, 1969) for the Marada Formation at outcrop in the Jebel Zelten and Marada regions, immediately to the west of the Phase 1 Area.

The distribution of total thicknesses of limestone, including dolomite (Map Figure 2c) shows a broadly antipathetic pattern to that of total sand. Maximum values occur in the north and north-east and minima in the south-west though here the area in which limestone is totally absent is small. The centre of the Area is marked by intermediate values and complex isolith patterns. The very low limestone thickness in the extreme north-west corresponds with the dominantly clayey sequence at Well No C1-119. Generally isoliths present a broad north-west to south-east grain though this is by no means as clear as in the map of sand thicknesses.

In contrast to the other two primary lithologies, maximum values for the total thickness of clay (Map Figure 3c) in the upper 500 ft (152 m) of the Marada Formation lie in the central north-west to south-east trending belt. Within this, highest values occur generally south-east of the centre of the Phase 1 Area with the exception of the isolated dominantly clayey sequence in the north-west at C1-119. Values decrease both to the north-east and south-west where particularly low values are located in the region of high sandstone content.

The distribution of anhydrite/gypsum bearing strata within the upper 500 ft (152 m) of the Marada Formation (Map Figure 4c) shows a clear distinction between the north-east and south-west of the Phase 1 Area. Evaporite bearing sediments are present throughout the north-eastern half of the Area but extend into the south-western half in Concession 80 and south-eastern Concession 59. Within the north-easterly evaporite-bearing zone, evaporites appear to be absent in certain areas. Although this variability probably results in part from the effects of superimposition, the difficulties of sampling in these rapidly drilled holes cannot be ignored and may well account for some of the more extreme variations.

Lithological variation in the upper 500 ft (152 m) of the Marada Formation may be summarised as follows. The region divides into three north-west to south-east trending belts. Over the north-eastern belt, the sequence is made up of limestones, dolomites and interbedded clays. In the centre lies a band of alternating sandstones, limestones and clays. Gypsum and/or anhydrite are widely developed over the whole of the former zone and part of the latter. In the south-west, limestones decrease in importance and the sequence comprises mainly sandstones and clays.

Comparison of the Marada Formation lithofacies pattern for the Phase 1 Area with that of the outcrop area immediately to the west (Selley, 1967, 1969), shows a marked degree of similarity. As a result of detailed sedimentological field investigations, Selley was able to distinguish five facies and relate them to their depositional environments. Four of the facies form laterally interfingering belts parallel to the palaeo-shoreline. Detrital limestones deposited as carbonate sand barrier beaches and offshore bars are succeeded landwards by lagoonal laminated shales. These interdigitate with interlaminated shales and sands deposited on tidal flats fronting a fluviatile coastal plain comprising crossbedded sands and shales. Calcareous channel-sandstones comprising the fifth facies cut through the other facies orthogonally to their trend and represent estuarine deposition.

The similarity both of broad facies relationships and of sandstone body trends suggest that Lower and Middle Miocene deposition in the Phase 1 Area took place in a similar shoreline complex. Only the trend of the shoreline appears to differ. In the Marada area the trend is east-west (Selley, 1969, p. 447) while in the Phase 1 Area it would seem to be north-west to south-east.

2.4.3.3. Post-Middle Miocene

a. Distribution and configuration of base of Post-Middle Miocene sediments

The outcrop of the Post-Middle Miocene sediments extends over all but the south-western third of the Phase 1 Area (Map Figure 7). The limit of the outcrop runs north-north-west from the south-west cornr of Concession 126, passes slightly to the east of Ain Zubairi and then around a north-easterly directed bulge to the north of Ain Sidi Mohammed to leave the eastern boundary of the Phase 1 Area in the north of Concession 6. The boundary presented on Map Figure 7 was established as a result of detailed appraisal and synthesis of oil company photogeological and photogeomorphological map compilations.

The configuration of the base of the Post-Middle Miocene sediments shows marked changes in elevation. Pronounced lows occur in the east, north-east and north of the Phase 1 Area, this last being particularly marked reaching depths in excess of 600 feet below sea level. A broad area of intermediate elevation extending south from the vicinity of the Amal Field to around the Gialo Field separates the northerly trough from those to the north-east and east. To the west and south, the basal surface rises steadily but is interrupted by several local north-easterly deepening depressions.

Comparison between the topography of Phase 1 Area (Map Figure 2) and the configuration of the base of the Post-Middle Miocene shows that the deep northwards trending trough in Concession 95 corresponds very closely with the site of a northerly trending topographic depression. This correspondence could reflect the influences of increases compactional effect in the thick Post-Middle Miocene sediments. Alternatively, or additionally, it could suggest that well-established tectonic subsidence trends continued to play a significant role in changing the present-day topography (cf. Wright and Edmunds, 1969).

b. Calanscio Formation (formerly termed the Upper Sands)

The Calanscio Formation consists mainly of medium to fine or coarse unconsolidated quartz sands occasionally pebbly grading in part to sandstones with pronounced calcareous cements and to sandy calcilutites. Sand grains are subrounded to subangular and frequently frosted. Grain size analyses show the sands to be moderately well sorted with size-frequency distributions which are positively skewed.

Interbeds of clay occur at well separated intervals throughout the formation and only very rarely exceed 15% of the total thickness. The clays are generally buff and grey in colour and commonly sandy, occasional grading to clayey sands and sandstones. Thin calcilutites may be associated with the clay beds. Anhydrite/gypsum, which is likely to be associated with the clays, has been reported from the Formation at a small number of oil company lithological logs.

No fauna has been reported from the formation. As regards depositional environments, the general lithology, the coarseness and the lack of fauna of the Formation suggest deposition in a continental alluvial plain environment in which fluviatile channel sedimentation was dominant. The interbedded clays could represent limited over-bank deposition while the thin fine-grained limestones suggest deposition in shallow ephemeral lakes.

In the well logs, the Calanscio Formation is best characterised by the gamma log which generally shows very low values reflecting the low clay content. Higher gamma values indicative of clays are restricted to well defined horizons, generally no more than 8 to 10 feet thick. Zones of intermediate values commonly occur in the upper part of the Formation and may be indicative of a dispersed clay content. Thin limestones, associated with clayey horizons, cause narrow peaks on the BHS logs. These contrast markedly with the generally low interval transit times of the bulk of the Formation which reflect a low degree of consolidation and cementation.

Regional synthesis has shown that in centre and south-east of the Phase 1 Area the configuration of the base of the Calanscio Formation (cf. Benfield 1972, Map 3; cross-section B-B') is that of a broad trough elongated in a north-west to south-east direction and deepening to the south-east. Within this trough the base is deepest in a similarly oriented basin in the east where it reaches over 300 feet below sea level. In the west a shallower, elongate but closed basin in which the base is deeper than 200 feet below sea level occupies the greater part of Concession 103. Over this area, the Calanscio Formation comprises the bulk of the Post-Middle Miocene.

To the north, the base of the Formation generally rises to around 50 feet below sea level along an east-west line approximately following latitude 29° 15' N. The steepness of much of the northern margin of the trough suggests that the boundary between the Calanscio Formation and the sandstones, clays and limestones of the underlying Aklash Formation could possibly represent a lateral facies change. To the north of this line, in northern Concession 95, the base of the Formation again falls to at least 180 feet below sea level in a northerly directed depression located on the site of the deep trough of Post-Middle Miocene sediments noted above.

c. Aklash Formation (formerly termed the Lower Unit)

Where thinly developed, the Aklash Formation comprises medium generally clayey sandstones and sands and interbedded clays. Where thickly developed, the Formation generally consists of fine to medium clayey sands and sandstones, sandy clays, clays and fossiliferous marine limestones. In some sections, clays are developed to the virtual exclusion of all other sediment types; in others, for example around A1-LP5C, sands and sandstones predominate. Anhydrite is recorded from one borehole.

In areas where the Formation is thin and comprises mainly clayey sands, gamma logs show intermediate values. Where it is thick, rather more variability is seen in both the gamma and BHS logs, reflecting the more heterogeneous nature of the sediments. However, average values are intermediate and in both cases clearly lower than in the underlying Lower and Middle Miocene sediments.

The age of the sediments is poorly known. The fauna from the Formation has only yielded a Post-Middle Miocene age. It is possible that it is of Upper Miocene, Pliocene or possibly even Pleistocene age.

The thickness of the Formation varies widely across the Phase 1 Area. Over much of the south-central part of the region, the Formation is thin, values of 5 to 10 feet being common, and even absent in some areas. To the north and east thickness increase rapidly. Maximum values of over 400 feet occur in the north of Concession 95 while values of over 200 feet are found along the eastern boundary of the Phase 1 Area in Concession 102 and 97.

Lithological changes are associated with the increase in thickness of the Aklash Formation (Benfield, 1972). To the north the total thickness of sands and sandstones increases sharply in contrast to the low and zero thicknesses over the greater part of the south-central part of the region. The change corresponds quite closely with the southern limit of limestone development in the Formation which suggests that the zone of sand deposition could be located along or adjacent to a shoreline trend. Only in the east is the increase in thickness of the Formation unaccompanied by significant sand deposition.

d. Basal Contact of the Post-Middle Miocene Sediments

Evidence for the character of the basal contact of the Post-Middle Miocene with the underlying Lower and Middle Miocene sediments stems from three sources. First, the marked change in lithology from the heterogenous interbedded lithologies of the Marada Formation (see below) to the generally more uniform lithology of each of the subdivisions of the Post-Middle Miocene suggests a marked time break at the basal contact. This is supported by the generally lower degree of cementation in the Post-Middle Miocene sediments. Second, the marked changes in elevation of the base of the Post-Middle Miocene and particularly the local north-easterly deepening depressions, suggest that a period of terrestrial erosion intervened between the deposition of two units (cf. Barr and Walker, in preparation). Finally, though no general stratigraphic subdivision of the Lower and Middle Miocene Marada Formation was attempted in these investigations, preliminary assessment of certain well-logs suggest that a correlation could possibly be established between neighbouring wells. These correlations, if upheld, would suggest in turn that in some areas Lower and Middle Miocene strata have been cut out at the base of the Post-Middle Miocene.

Thus the evidence indicates that basal contact to Post-Middle Miocene is unconformable in nature. This has important hydrogeological implications. Flow from the Lower and Middle Miocene to the Post-Middle Miocene is generally inhibited in a vertical direction by the presence of interbedded clays in the former. However, the effect of the unconformity could be to bring permeable beds within the Lower and Middle Miocene into contact with the base of the Post-Middle Miocene and so permit flow between the two.

2.5. HYDROGEOLOGY

An aquifer is defined as a saturated formation capable of development. In the Phase 1 Area, aquifers occur in the Post-Middle Miocene and in the older Miocene and Oligocene formations.

The P. M. M. aquifer is a relatively thin body which occurs essentially unconfined under steady state natural flow conditions but behaves in more complex semi-confined fashion during short term abstraction periods in consequence of interbedded impervious or semi-pervious clay layers. The Miocene and Oligocene is a multiple system which includes an upper unconfined section in outcrop areas but is confined elsewhere. It is logical at this stage to consider the P. M. M. and the Miocene/ Oligocene as two aquifer systems, sufficiently distinct to be treated separately but with some inter-relationships which are locally important.

In the Phase I Area, the outcrop boundary of the Post-Middle Miocene occurs to the west with a north-south trend; the Miocene and Oligocene formations dip below and to the east at a shallow angle (Map Figure 5). The Post-Middle Miocene aquifer occurs at shallower depths, is more accessible and over significant areas of Phase I contains water of better quality than in the Miocene and Oligocene formations. For these reasons the detailed studies during the past two years have been concentrated on the former aquifer, aimed at evaluating its potential. Discussion of the latter system is based on limited data and is intended to indicate possible potential for future consideration and investigation.

2.5.1. Miocene and Oligocene Aquifers

The aquifers in the Miocene and Oligocene formations occur within a thick and complex series of which comparatively little is known. The Oligocene is predominantly a sandstone/ shale sequence with subordinate carbonates and shale content increasing to the north. The Miocene is predominantly of carbonate and shale to the north-east and north of the Phase I Area with increasing proportion of sandy carbonates and sandstones to the south and south-west.

In consequence of the easterly dip of the strata, the water table below the outcrop area occurs within successively older horizons to the west and south-west down into the Oligocene in the extreme south-west corner.

The total saturated thickness below the Phase I Area is least in the south-west, thickening to the east and north. The general range is between 1300 and 2300 feet approximately. Depth from ground surface to the water table ranges from zero in the vicinity of the Hutaytat Al Fawziyah sabkhat in the north to 550 feet in the south-west corner.

A number of shallow wells generally less than eight hundred feet deep have been drilled in the aquifer system in the western Phase I Area and the piezometric contours shown in Map Figure 9 are based on their measured water levels. All information shown is from wells occurring within the Miocene. Gradients are northwards and by comparison with the regional piezometric map Map Figure 8, it can be seen that the trend basically continues that in the Oligocene which continues to outcrop farther to the west. This general consistency indicates that flow lines are probably parallel to the gradient. In the Phase 1 Area, the piezometric contours in detail show two diverging gradient trends with dips to the north-east and north-west, indicative of discharge in those directions. To the north-west, discharge is known to occur in the Hutaytat al Fawziyah and in other sabkhats nearer the coast. Discharge to the north-east presumably occurs at the sabkhats to the south-east of Agedabia where the Miocene again outcrops; it may also occur by leakage into the Post-Middle Miocene aquifer in the Phase 1 Area and this aspect requires careful consideration.

The Miocene aquifer system occurs confined to the east of the P. M. M. outcrop boundary and in the central area, the piezometric contours transect those of the P. M. M. aquifer at steep angles converging to a subparallel trend farther to the south. The hydraulic head difference along the central boundary zone ranges from 125 feet to 50 feet, decreasing southwards and with higher values within the Miocene aquifer. The relations, i. e. head differentials and changing piezometric trends both suggest an absence of intercommunication between the P. M. M. and Miocene aquifer along the central boundary zone but with progressive and increasing continuity towards the south. The absence of intercommunication in the central zone is confirmed by geochemical differences; the developing continuity is in accord with the changing lithology of the Miocene with increasing proportion of sandstone to the south. Where a head difference occurs along the southern boundary, lateral leakage is probable and the inference is supported by the steady state model construction which required leakage to obtain the necessary piezometric configuration.

A number of deep wells in the confined Oligocene aquifer system have been drilled at Occidental A and D Fields, Concession 103 at Gialo E Field Concession 59 and at Nafoora G Field, Concession 51. Basic details are shown in Table 5. Considering first the piezometric levels in Occidental's A and D Fields, which occur in the central Phase 1 Area, it is apparent that these are variable but always above levels in the overlying P. M. M. aquifer but generally lower than the adjacent contour values in the Miocene aquifer to the west. The higher values indicate a shallowing continuity with the north-easterly gradient trend and suggest no significant upward component of flow which would suggest leakage into the P. M. M. aquifer. The lower values are almost certainly the result of leakage through corroded casings and the supposition has been confirmed in a number of wells by temperature logging. It should be noted that the perforations in these deep wells are considerably deeper than those in the Miocene aquifer to the west. Nonetheless, the apparent continuity of trend does suggest an absence of upward leakage in the central Phase 1 Area and the geological relations support the probability since there is an abundance in clay in the sequence.

Upward leakage into the P. M. M. aquifer in the north and east of the Phase 1 Area should also be considered since a head differential exists and leakage would supply a convenient explanation for some of the anomalous highly mineralised waters with occur there.

The presence of gypsum and anhydrite with reduction of clay content in the Miocene in these areas provides supporting evidence but the limited data on geochemical trends do not confirm.

2.5.2. Post-Middle Miocene Aquifer System

The P. M. M. formations outcrop over the eastern two-thirds of the Phase 1 Area. The depth to the water table can be determined by combining Map Figures 2 and 9. It is a maximum in central 103 on the western side of the outcrop area where it exceeds 300 feet, and decreases to north, south and east. Lowest values occur in the general region of Jalu oasis where it is only a few feet below ground surface.

The saturated thickness is shown in Map Figure 7c [values in metres]. On account of the low gradient of the piezometer contours the form of the aquifer corresponds generally to the contours of the base of the P.M.M. [Map Fig. 7]. From the western margin, the thickness increases generally eastwards, modified by two subsidiary troughs. Maximum saturated thickness occurs on the eastern margin of the Phase 1 Area where it exceeds 590 feet [180 m]. Main saturated thickness is in the range 260-430 feet [80-120 m]. The main subsidiary trough extends from south to north from central Concession 103 through Concession 95.

In considering the characteristics of the Post-Middle Miocene aquifer, the relations between the upper and lower stratigraphic units [Calanscio and Aklash Formations] exert a critical influence. The lower unit which consists mainly of clays, clayey sands and sandstones has a lower permeability than the upper unit of sands with subordinate interbedded clays. The lower unit has a negligible thickness to the south of latitude 29° N [generally less than 15 feet], but increases rapidly in thickness farther north. On account of the east-west strike and northerly dip of the piezometric contours [Map Fig. 9], the aquifer occurs primarily within the upper unit to the south of latitude 29° N and within the lower unit to the north of this latitude. At J [A1-LP3C] for example which is located approximately at latitude 29° 6' and longitude 20° 31', the water table coincides with the junction between the two units.

The gradient of the piezometric contours in the P. M. M. aquifers is of the order of 1 in 10 000 on the west side down to 1 in 20 000 on the east. Despite the lower permeability of the Aklash Formations, there is no significant change in gradient on the west side to the north of latitude 20° which may be accounted for by the increase of saturated thickness giving a compensatory increase in transmissibility. The lower gradient on the east side is presumably a reflection of a higher transmissibility.

2.5.2.1. Aquifer Characteristics

a. Definition

The rate of flow through a porous medium is proportional to the head loss and the permeability (or hydraulic conductivity, K) and inversely proportional to the length of the flow path. K is a constant which is equal to the volume of flow per unit cross-section area under unit gradient [m^3 per m^2 per day = m/day]. Transmissibility defines the ability of the total aquifer to transmit water and is equal to the average permeability times the aquifer thickness [m^2/day].

The storage coefficient/specific yield are dimensionless units defined as the volume of water released or stored per unit surface area of the aquifer per unit change in the components of head normal to that surface. The storage coefficient (S) refers to a confined aquifer and its magnitude is related to the elasticity of the aquifer material and of the enclosed water. The specific yield (Sy) refers to the unconfined parts of the aquifer and is equal to the effective porosity or the volume that can be drained under gravity from the pore space.

Permeability can vary in space in consequence of anisotropy and larger-scale lithological variations. Transmissibility may vary not only in space but also in time such as, for example, by reduction in aquifer thickness in consequence of abstraction. Storage coefficient/specific yield may vary also in space and effectively in time. Significant aspects of such changes include movement of the water table and permanent withdrawals from storage in non-elastic clay layers.

b. Analytical Methods and Boundary Conditions

The methods employed to determine the aquifer characteristics have included unsteady-state analysis using short duration pumping tests [5-10 days] and steady-state analysis with model techniques and equilibrium flow patterns.

c. Unsteady State Analysis

Aquifer tests have been mainly carried out in the central area of the P-M. M. outcrop where the aquifer is constituted largely of the upper unit (Calanscio Formation) of sands with thin interbedded clays. The base of the aquifer in this area is constituted of a well-defined clay layer commonly between 10 and 20 feet thick which corresponds to the Aklash Formation. The full lateral extent of the various intermediate clay layers is uncertain but in nearly all cases they do extend sufficiently to control drawdowns in the immediate vicinity of a pumping well for a test of short duration.

Test procedures have been described (section 2.3 on Methods) and consist basically of pumping from a well screened in the lower section of the aquifer, with drawdown observations being made in piezometers located at varying distances and levels. [Text Figure 4a]. Drawdowns in the piezometers at pumping screen levels have followed a leaky artesian pattern with reduced drawdowns or no drawdown at all occurring in piezometers located at levels above the screened interval [Text Figure 4b and c]. In the latter case, it is deduced that the transmissibility of the upper section was of sufficient magnitude in relation to head changes at the intervening clay layer to result in drawdowns lower than measurement limits; in the former case, the reduced drawdowns can be attributed either to the effects of vertical flow and leakage through the intervening clay layer, or to vertical flow effects consequent upon the proximity of the pumping well occurring within an essentially single unconfined body [Text Figure 4d]. In only one of the sites tested (JD) is the latter condition believed to occur.

The conditions operating at the various test sites have differed in detail. In all cases, a significant clay layer occurs at the base of the P. M. M., and upward leakage during the test has been discounted. The aquifer is in effect a multiple body with a surface unconfined layer overlying one or more confined layers below, thus departing somewhat from the simplified patterns shown in Figure 4a-e. The screened section in the pumping well may or may not extend over all the confined layers. In the latter case, measurements of drawdown in the overlying confined layers as well as the uppermost unconfined layer would have been desirable.

Leaky artesian analysis presupposes no drawdown in the overlying aquifer above the leaky layer, and as the observed drawdowns were either negligible or small in relation to thickness, this condition is held to have been met. The value of transmissibility thus determined will relate to the thickness of the lower 'effectively' screened section, i.e. from the base of the aquifer to the lower level of the first clay layer above the screen, assuming that the difference in level between the upper screen and clay is not great. This section is termed the 'responding' section. Values of storage coefficient determined were all in the artesian range as is to be expected.

The method of analysis utilized is regarded as satisfactory within certain limits. It is thought in most cases to have provided a reasonably accurate value of transmissibility in relation to horizontal flow for the responding section of the aquifer, and also a value of the artesian storage coefficient. It will not provide a value of specific yield, total transmissibility or an indication of anisotropic permeability. Anisotropy is to be expected in consequence of stratification of clay material, either dispersed or layered. A value of total transmissibility has been determined by extrapolation of the results using sieve analysis data for the upper (non-responding) section(s) above the leaky clay layer. For the purpose of this report, a simplified correlation has been attemped (see section below); in the final report a more detailed correlation is proposed.

Other possible sources of error may occur in consequence of restricted screening in an observation piezometer, or varying abstraction over the screened interval. An error due to the former circumstance is thought to have occurred at site JA drawdown observations during the test were limited to measurements in the two existing water wells which are screened for a short section near the base of the aquifer. The apparent value of transmissibility is considerably higher than is thought probable and it is considered that the drawdowns observed relate to a limited subsection in the lower part of the aquifer between two intermediate clay layers [Figure 4e].

These drawdowns would require to be correlated with the flow through the screen opposite the subsection of the aquifer in which the piezometers are located, and the analysis would then provide a value of transmissibility for this limited thickness. The total flow rate on the surface cannot be subdivided according to length of screen or probable permeability since localised factors may also exert an influence. Variations are known to occur which cannot readily be explained. At JE for example, the upper screened section is opposite coarser sand which would be expected to have higher permeability. The down-hole flow velocity log did, however, show that over 90% of the flow came from the lower two thirds of the screened section. Due to equipment failure, it was not possible during the pump test at JA to run a depth velocity log and in consequence the drawdown measurements cannot be analysed to provide a true value of transmissibility.

d. Results of Unsteady State Analysis

Drawdown and recovery data were analysed by Theis and leaky artesian type curves of $1/u$ versus W(u) or W(u, r/B), and by the Jacob-Cooper semi-log plots. The latter were commonly of lesser application due to the time abscissa infringing either on the period before the log approximation became valid or on the period after departure from the Theis curve. Distance-drawdown plots were also used if sufficient data was available in the same limited period when boundary conditions were appropriate. Full details of the results are shown in the individual site reports (Appendices 1 to 11), but the tabulated data of aquifer characteristics shown in Table 6 are based mainly on the average values derived from the log-log plots, since these are considered to provide more accurate results. For the final report, a more detailed fuller discussion of individual results and analysis will be provided using also the Hantush (1967b) solutions for aquifers separated by impervious layers and in which drawdown occurs in the layer overlying the leaky interface. It is not considered however that much inmprovement in the determined values of transmissibility and storage coefficient will be obtained, since the degree of observation is not sufficient to evaluate vertical anisotropy. The method will be mainly employed by substitution of estimated Kh/Kv ratios [Kh = horizontal permeability and Kv = vertical permeability] with appropriate modifications in an attempt to correlate with observed drawdowns and hence to provide a more accurate prediction of long-term pumping drawdowns.

The symbols used in Table 6 have the following explanations:-

rt : thickness of the responding section of the aquifer based on leaky artesian analysis assumptions, i.e. drawdowns relate to local confined section adjacent to screened interval.

rte : thickness of the responding section minus thickness of discrete clay layers occuring within the responding section.

T : the average value of transmissibility from the more reliable results.

K : T/rte = permeability.

ut : thickness of non-responding [usually upper] section of aquifer.

[NB. In C1-95, the upper aquifer was in fact tested and ut etc., refers to the lower unit which was tested only for water quality.]

ute : thickness of non-responding section minus thickness of clays/calcilutites.

tte : total effective thickness [= rte + ute].

Te : total transmissibility.

st : total saturated thickness [= rt + ut].

Ka : apparent permeability [= Te/st].

SC : specific capacity observed.

Eff : efficiency based on ratio of observed and calculated specific capacity [using T].

S : mean storage Coefficient corresponding to T.

Mean Deviation : refers to deviation of the various results from the mean values (T), assuming all are positive.

e. Steady State Analysis: Digital Model Study

1. Regional Input Data

i Static water level [Map Figure 5c]. This map is based on a hand-drawn water table contour map of the Post-Middle Miocene aquifer. The map used was an earlier version to that shown in Map Figure 9 and differs in detail mainly in the northern and eastern marginal areas. Map 5c was prepared by superimposing a model grid on the hand-contoured plot from which the model values were read off and incorporated into the computer data cards.

ii Aquifer Transmissibility (Te). The values used were preliminary estimates which differed somewhat from the more considered results shown in Table 6.

iii Base of the Post-Middle Miocene Aquifer [Map Figure 20c]. The Map was derived in like manner to Map Figure 5c using an earlier version of Map Figure 7. Map Figure 20c was used primarily in conjunction with Map Figure 5c to determine the western boundary of the saturated aquifer, i.e. the intersection of the water table with the base of the aquifer.

Each node was considered to be a block of the aquifer 4.5 km x 4.5 km x (depth of saturated aquifer at the centre of the node). Reference in this report to the water level of a node indicates the value at the centre point of that node. Boundary flows to or from a node are considered to apply to the node as a whole and may be from another aquifer (below) or the same aquifer (adjacent). Intersections of the grid lines indicate the mid points of nodes. Each of the nodes for the Post-Middle Miocene aquifer was assigned a set of values of parameters as follows:

Easting E
Northing N
Initial Water Level V (from static water level Map Figure 5c)
Transmissibility T (Estimated from pumping tests, extrapolating where necessary)
Boundary Flow BF (Estimated from water table gradient and transmissibility)
Nodal Type Index J (J = 1 in aquifer, J = 0 outside)

2. Model Operation

Initially the Boundary Flow was set to zero everywhere except along the northern and southern boundaries. The water level map indicated that the eastern boundary could be considered as a flow line as the water level contours are roughly perpendicular to the boundary. Very approximate values of T and BF were required initially.

A water balance equation was set up for each node in turn using values of water levels between adjacent nodes to calculate the gradients and transmissibility to compute flow rates. New values of water level were calculated from these finite difference equations for each node in succession and the set of calculations for the whole network was repeated many times (iterations) until the levels obtained at all nodes were not changed significantly by further iterations. This result was the steady state solution for the water levels of the model; it differed somewhat from the actual steady state water levels observed in the aquifer by up to $\pm$ 20 metres.

The next stage in the modelling procedure was to adjust the input parameters to the model (transmissibility, boundary flow) in order to make the steady state model conform closely to the observed steady state conditions. The main adjustments made to this steady state model were to the boundary flow and transmissibility. It was found necessary to include some flow from the Lower and Middle Miocene aquifer in the south west; there is some chemical evidence to support postulated flow from this direction. The results of the steady state model after about 12 sets of adjustments is shown in Map Figure 6c. It may be seen that this interpretation agrees closely with the observed static water levels of Map Figure 5c. The final values of transmissibility, permeability and boundary flow used to produce this steady state model are shown in Map Figures 8c, 9c and 6c.

A comparison of the model values of transmissibility [from Map Figure 8c] and the local pumping test deriviations is shown in Table 7. In considering these results, it should be recognised that the model values will relate more to regional transmissibility and the pumping test derivations to local transmissibility. The values are unlikely to correspond closely unless the aquifer is extremely uniform. The comparison does, however, offer some measure of assessment of the validity of both sets of results.

Significant differences occur mainly at JA, JB and JC. The pumping test results at JA are known to be suspect for reasons already given. The differences at JB and JC are less easy to explain but it can be assumed that they do represent differences between regional and local values. At JB, the aquifer rapidly thins westwards which may account for the difference. No ready explanation can be offered for the difference at JC except that here there is an absence of significant high level clay layers and the calculated transmissibility values may be anomalously high due to vertical flow effects.

3. Model Construction

The model assumed that the vertical permeability was uniform and equal to the horizontal permeability at any one location. The model extends over the Phase 1 Area and is divided into a grid of 46 x 45 nodes [Map Figure 14c].

2. 6. HYDROGEOCHEMISTRY

2. 6. 1. Introduction

A programme of geochemical investigations was carried out during the Phase 1 Area study with the following objectives:

1. To determine the three-dimensional water quality distribution in the aquifers of main interest.

2. To identify the principal hydrogeochemical units and relate these to the hydrology and geology and thence to establish the relationship between the various types of groundwater.

3. To establish the chemical suitability of the water for domestic, agricultural or industrial use (including likely corrosion effects on well casings and installations).

The Phase 1 Area is centered on a north-trending freshwater lobe which was proved in earlier studies. This lobe is bounded on the east, north and west by zones of inferior quality water. In previous reports the regional appraisal had not recognised the significance of a lateral quality change between the Post-Middle Miocene and deeper aquifers, and although some interlationship may exist, these two aquifer systems should be treated separately.

The Post-Middle Miocene (P. M. M.) aquifer can be treated effectively as a single aquifer, as discussed in the section on hydrogeology, but the Miocene and Oligocene sequences include several aquifers. In this report the main emphasis is on the PMM aquifer in which all the exploration drilling took place, but quality reconnaissance of the deeper aquifers was made where sampling was possible.

The overall quality changes are represented in Map Figure 11which shows the total groundwater mineralisation in the two aquifers expressed in milligrammes per litre (mg/1). This map is a two dimensional plot of a three dimensional pattern which will be clarified by cross sections and maps of individual constituents to be presented with the final report. The geochemical variations must be considered in relation to topography, hydraulic gradient and geology in addition to anomalies caused by variations in well depth.

2. 6. 2. Miocene and Deeper Aquifers

2. 6. 2. 1. Water Quality Distribution in the Miocene Aquifers

The amount of data on groundwater in the Miocene Formations is limited and the results must be assessed with some caution. No exploration drilling in these aquifers was carried out during the Phase 1 studies and although existing water wells in the west and south-west are of similar depth to those in the P. M. M. aquifer, many in the north-west are much deeper with multiple perforations.

Mineralisation in the area of outcrop Miocene increases towards the west at an acute angle to the flow direction, and the main control therefore should be geological. Total mineralisation immediately adjacent to the P. M. M. aquifer may be less than 1000 mg/1 but increases westwards to over 3000 mg/1.

2. 6. 2. 2. Quality Changes with Depth

Little information is available on quality changes with depth as all existing wells are open at the same general level. The changes which do occur are gradational and are probably therefore mainly lateral variations. The situation will be more readily apparent from the cross-sections which will accompany the final report. The local anomalous high values which occur in the springs around the Hutaytat at Fawziyahdepression are the result of current evapotranspiration and therefore untypical of the water at depth.

2. 6. 2. 3. Confined Groundwater in the Miocene/ Oligocene Formations

Deep wells (300-1000 m total depth) are developed in Miocene/Oligocene formations beneath the Phase 1 area, notably in Concessions 103, 59 (Gialo) and 51. Some of the chemical data are included in Map Figure 11 and other data are tabulated in the Appendix of chemical data. These waters will be discussed in more detail in the final report, but it is clear that some of this water may be of reasonable quality (around 5000 mg/1) although considerable variety in composition is found.

2. 6. 3. Post-Middle Miocene Aquifer

2. 6. 3. 1. Water Quality Distribution

In comparison with the Miocene there is considerably more data on the P. M. M. aquifer; not only is there a greater density of existing water wells, but the test drilling which has been carried out has provided valuable up-to-date evidence.

Present studies have defined the extent of the fresh water lobe with some accuracy and shown that it contains water with a very uniform chemical composition. This was confirmed by conductance logging and by test pumping in which no significant compositional change was detected in any well for the duration of the test. There is an overall quality change from the south of the area (1000 mg/1) to 2000 mg/1 over a distance of some 130 km. The direction is down gradient and this increase is likely to be the result of increasing flow time within a relatively uniform lithology.

There is a relatively rapid quality change north of 29° 20' N in the direction of flow, most probably the result of lithological changes, although in this relatively low-lying area secondary processes may also be responsible.

To the east there is also a relatively sudden water quality transition at right-angles to the hydraulic gradient, which was discussed in the earlier reports. Water in this area has a different ionic composition to that in the main lobe. In general water quality relationships in the east of the Phase 1 area appear to be complex, with alternating north-tending, longitudinal zones of fresh and poorer quality water. To appreciate the changes fully the three-dimensional picture must be considered.

2. 6. 3. 2. Water Quality Changes with Depth

There appear to be no major quality changes with depth in the central fresh water lobe of the P. M. M. aquifer, pointing to a high degree of hydrogeological homogeneity in this proposed development area.

Specific electrical conductance (SEC) logging during the exploration programme revealed minor quality stratification e. g. at JE-01 where a skim of fresh (SEC = 2500 micromhos) water overlay water with SEC of 2800 umhos, and also at JC-01A. The only other significant quality changes were found where wells had been developed in the lower unit of the P. M. M. aquifer or where they were apparently perforated both in the P. M. M. and Miocene aquifers.

Quality deterioration in the east, south of 28° 50' N., takes place in an area where the water table is relatively deep and is considered to be related most probably to in-situ geological conditions or to fossil drainage or evaporation patterns; there is in fact some evidence for both.

North of 29° 00' N the situation is more complex for in addition to the factors mentioned above, other possible influences include the effect of contemporanious evapotranspiration and/or the recycling of irrigation water. North of this latitude water quality of 6000 mg/1 is common and may reach as high as 10 000 mg/1.

At Augila oasis, near surface water was found to be locally quite mineralised but this is considered to be superimposed on the regional trend of deterioration to the north-east and it is very likely that an improvement in quality would be found with depth.

At Jalu oasis the same effect is found but here the regional deterioration is more advanced and except on the south-west side of the oasis, where quality in shallow wells is better than in the east, it is probably that no great quality improvement would be found with deeper drilling. Quite sharp lateral changes are found even in the shallow groundwater, for instance in 102-D field where the quality changes from 2500 mg/1 to around 10 000 mg/1 over a distance of 1 km. Further analysis of the geochemical data including stable isotope analysis may resolve the causes of this and similar abrupt changes in this region, but the balance of evidence shows that the ionic composition in both good and poor quality water is similar and therefore that concentration by fossil or recent evapotranspiration is the more likely explanation. Upward leakage locally of more saline water from the P. M. M. aquifer may also be a possibility, but leakage upwards from the Miocene seems not to be indicated on geo-chemical grounds.

At Gatmir oasis fresh water (2000 mg/1) is found near the surface. This water is thought to be related to recent drainage patterns.

2. 6. 4. Principal Hydrogeochemical Changes in the Phase 1 Area

Representative chemical analysis from the Phase 1 area have been plotted on a trilinear diagram (Text Figure 5) to illustrate the principal compositional trends in the Miocene and P. M. M. aquifers. The main features are as follows:

1. Good quality water (1000 mg/1 in the Miocene in the south of the area e. g. Wells 461, 449) has a fairly well defined Na Cl (SO_4) composition with Mg > Ca.

2. Beneath the P. M. M., the Miocene water (e. g. J(A1-LP5C) long string and sample 302) tends to become sulphate enriched.

3. With the exception of J [C1-95]A which penetrates the P. M. M. Lower Unit all waters pumped from Phase 1 drilling sites fall into a restricted compositional field (Figure 5) with Na $\geq$ Ca+Mg; Ca = Mg and Cl $\geq$ SO_4 > HCO_3.

4. The higher salinity water to the south-east and north of Jalu has a different ionic composition, having Cl > SO_4, compared with the fresh water of the main lobe. This ionic composition is maintained as the mineralisation

increases for example along flow lines from Concession 97 (samples 511, 512, 513) through (152) to Jalu oasis and then to the Augila Field. The abrupt change in composition in Augila field takes place without any significant shift in ionic composition (compare samples 137 and 186).

5. Following flow lines from the east of the fresh water lobe [J(F1-97)] through Augila oasis towards Amal field (301,433) it can be seen that the mineralisation increase from the fresh water lobe appears to be related to an increase in sulphate (samples 297 and J(C1-95)A.

Most of these trends can be related to lithological changes within the P. M. M. aquifer, to difference in permeability or to surface effects and the relative importance of each will be dealt with in the final report. However within the P. M. M. aquifer two main hydrogeochemical units can be defined - the main lobe where ionic compositions are remarkably uniform and the eastern unit where chloride is the dominant anion. The variations in detail of the various major ions together with minor element variations will be covered in the final report.

2. 6. 5. Interrelationship between Miocene and P. M. M. Aquifers

Groundwater quality in the area of outcrop Miocene deteriorates at right angles to the main northward flow direction. From studies of the trace element analysis, notably strontium, a change in chemistry in the flow direction element was detected, related apparently to the change from arenaceous to calcareous facies within the Miocene. There is a discontinuity in this geochemical field when followed eastwards across the P. M. M. boundary in the central Phase 1 Area and this plus other evidence tends to indicate that significant lateral movement of Miocene water into the P. M. M. aquifer in this vicinity is improbable. In the southern Phase 1 Area this distinction is not apparent and geochemical evidence does not rule out the possibility that leakage between the aquifers may be taking place.

2. 6. 6. Age of the Groundwater

Samples were taken at several sites, including shallow wells in the vicinity of Jalu oasis for tritium analysis to check whether any recent recharge was indicated; all the results (not included here) were below limits of detection indicating that no component of post-1953 water was present in the samples. Final carbon - 14 results were not available at the time of writing but preliminary results do show a significant pattern. Eight of the thirteen samples analysed were below limits of detection (at least 36 000 years) but four of the remaining samples from the Phase 1 fresh water lobe gave uncorrected ages between roughly 20 000 and 34 000 years. Age stratification almost certainly exists and the pumped samples analysised probably represent an age mixture. Water from E1-105 however will give a final age of around 10 000 years which would provide strong evidence that the subsidiary fresh water lobe in the south-east of the area is the result of more recent local recharge. Stable isotope results, when available, should reinforce the Carbon-14 evidence and these, together with Carbon-14 data or fossil organic debris collected at the surface, should help to solve the recharge history of the area.

2. 6. 7. Quality in Relation to Use

2. 6. 7. 1. Domestic Use

The maximum permissable limit for total dissolved solids in drinking water according to international (WHO 1971) standards is 1500 mg/1. This level is reached or exceeded in parts of the fresh water lobe defined by the 2000 mg/1 contour, in the Phase 1 Area. In much of Libya drinking water of higher concentration is tolerated however by adaption, and local wells at Augila and Jalu with total solids up to 6000 mg/1 have been used at least until recently; the present water supply for Jalu obtained from Gatmir has a total dissolved solids of 1953 mg/1. Therefore it is desirable that the least mineralised water in the Phase 1 area occurring mainly in the south, should be considered first for domestic use, but the potential reserves should include all water below 2000 mg/1 total mineralisation. A maximum sulphate concentration of 400 mg/1 is recognised by the World Health Organisation. Most wells in the fresh water lobe, pumped during current investigations (see Appendix 11) gave values between 3050 and 600 mg/1 SO_4 and are therefore rather higher than might be desired for drinking purposes.

Minor element concentrations are generally very low. Trace metals in the pumped samples are well below the international health limits. Fluoride is slightly higher than optimum levels for dental health (0.7 - 1.0 mg/1) in most of the pumping wells sampled and is commonly in the range 1.3 - 1.8 mg/1; some minor dental mottling might therefore be expected. Nitrate levels are generally below 50 mg/1 NO_3 with JE-P, J(A1-LP$_3$C) and J(F1-97) slightly above this level. Nitrate levels in some parts of Cyrenaica are high and this problem was discussed in a regional context as a supplement to the original report (Wright and Edmunds, 1969).

It is recommended that nitrate levels are monitored regularly during any development to ensure that the level (100 mg/1 NO_3) is not exceeded. No bacterial analysis were carried out during this survey and suitable tests should be made during subsequent development.

2. 6. 7. 2. Agricultural Use

There is no single upper limit of total mineralisation for water for irrigation use, but the maximum limit will depend on soil type, permeability, crop types and ratios of ionic constituents as well as in total salinity.

Sodium absorption ratios have been calculated for all groundwaters where mineral analysis was made and are included in the Appendix. This ratio is proportional to the exchangable sodium in the water and the lower the ratio, the less susceptible is the water to alkali hazard. Most values for groundwater in the Phase 1 area lie between 4 and 6.5 which are relatively favourable for development. The salinity of the groundwater however presents obvious problems for irrigation, except where the water is used on highly permeable soils. Free drainage over much of the area of fresh water may however be hindered by the rather extensive calcrete deposits found in some areas.

Boron was determined on all pumped samples plus representative waters elsewhere within the Phase 1 area. Most groundwater in the central freshwater lobe contains about 0.5 mg/1 B (see Appendix 11), but becomes much higher in the more saline waters. The groundwater 0.5 mg/1 value approaches the limit where some toxicity to sensitive crops may occur and it could be that higher effective concentrations may be created within the soils with evapotranspiration.

The regional hydrogeochemistry relevant to agricultural development will be dealt with more extensively in the final report.

2. 6. 7. 3. Corrosion and Encrustation

Measurements were made throughout the field programme of various parameters necessary to define the chemical equilibria and corrosion properties of the groundwater. All results are given in Table 7; most refer to pumped samples during Phase 1 test pumping, but additional measurements were made on pumped samples in the P. M. M. aquifer plus two deep Miocene/Oligocene wells in Concession 103.

Field pH. , HCO_3 and temperature readings together with the chemical analysis were used to derive the carbonate equilibrium relationships (Back 1960). For most wells in the P. M. M. aquifer the equilibrium - free CO_2 is low [less than 15 mg/1] with two exceptions and is therefore not likely to be a serious factor in corrosion in waters where the pH is well above 7. The observed and theoretical ion activity products (K_{iap} and $K_{calcite}$) for the calcite equilibrium were computed and compared with each other in order to derive the extent of calcite saturation in the aquifer. A range of conditions in the P. M. M. aquifer is indicated and most waters appear to be supersaturated with respect to calcite. It is unlikely that downhole encrustation would occur unless airlift pumping is carried out as the precipitation would only take place concomitant with a serious change in physical conditions compared with those existing in the aquifer. However the results do mean that encrustation of transit pipes etc. , could occur.

Results for EH (redox potential) and pH have been plotted on a stability field diagram (Figure 6) where the actual data can be compared with the most likely theoretical stability of iron minerals and dissolved species (Hem and Cropper 1959). All groundwaters from the P. M. M. aquifer, except JC-P, fall just inside the field of oxidising conditions and $Fe(OH)_3$ stability. The low $Fe(HO)_3$ solubility should maintain the iron in solution at < 0.05 mg/1 and assist the formation of protective iron oxide coatings on well casings. Water from JC-P together with the Miocene/Oligocene deep wells in Concession 103 fall in the field of Fe^{2+} stability. These reducing groundwaters are capable of containing much larger amounts of iron in solution, will be aggressive to steel and prevent the retention of iron oxide coatings. Despite reducing conditions, however total Fe in JC-P was still very low, although a maximum of 3.8 mg/1 was found in the deep wells (Table 5). The proximity of the P. M. M. waters to the oxidation - reduction boundary might mean that fluctuations in the properties of the waters during sustained pumping might occur and thus the relevant parameters should be further monitored if development takes place. The existence of oxidising conditions in P. M. M. groundwaters in Concession 103 at the present time, some of which have been pumped for over 6 years, suggests that mild oxidising conditions are probably common in the P. M. M. aquifer.

2.7 WATER RESOURCES OF THE PHASE 1 AREA

Total water resources can be calculated on the basis of the area of aquifer extent, saturated thickness and effective porosity. Some indication of water quality is also desirable and it may be noted that in the Phase 1 Area, approximately 160 000 sq km is underlain by saturated formations whose upper few hundred feet contain water with total dissolved solids in less than 2000mg/1.

2.7.1. Miocene/Oligocene Aquifers

No detailed analysis has been prepared on these aquifers but some general assessments can be attempted on the basis of the available information. Water quality is likely to be major restrictive factor for agricultural, domestic and industrial use in areas to the north of latitude 28° 40' N except in the shallow unconfined Miocene. This assessment is based on the limited data from the deep wells in the Occidental A and D, Nafoora and Gialo Field Areas, and on the general lithological features. Data on water quality in these aquifers to the south of this latitude is limited to measurements in a few scattered relatively shallow wells, which show it to be of moderate quality (800-3000 mg/l). There is a reasonable likelihood that this general order of quality may be maintained in depth since both the Oligocene and Miocene Formations in the southern Phase 1 Area consist predominantly of sands and sandstones. The supposition has been confirmed by the results of test drilling at Q1-65, to the south of the Phase 1 border. However any proposal to withdraw large supplies from these aquifers would require a comprehensive drilling and aquifer testing programme in order to make a reliable resources estimate.

2.7.2. Post-Middle Miocene Aquifer

A realistic assessment of water resources can best be made by imposing various practicable abstraction schemes on the aquifer and obtaining predictions of subsequent changes in water levels and water quality. Two such schemes have been prepared for this report making use of the steady-state computer model and incorporating the additional boundary conditions required for unsteady state analysis. Possible water quality changes during the time periods tested have been discounted. A discussion of this factor will be included in the final report but in view of the site selection for the abstraction fields in the main area of good quality water it is unlikely that significant changes will occur for a considerable time period. Other effects are likely to exercise more control. In this context it should be noted that it is assumed that poorer quality water will tend to move laterally in the P.M.M. aquifer. The base of the aquifer is considered to be effectively impermeable preventing inflow from below. This is a reasonable assumption in the central Phase 1 Area where the well fields are located. Departures from this condition are probable in the southern Phase 1 Area but the feature gives no serious concern since the deeper aquifers in this location probably contain water of equivalent quality.

For the unsteady state analysis it is assumed that the P.M.M. aquifer will behave as a single, unconfined body with varying lateral transmissibility, vertical uniform permeability, and with a specific yield of 10%. No account has been taken of the possible effects of the low permeability clay layers within the aquifer even though they resulted in leaky artesian conditions occurring during the short term pumping tests. It is assumed that the regional water level changes will correlate with unconfined conditions with corresponding storage release (specific yield). Some evidence for this condition has been observed in recent work in Cyprus (Kitching, 1973). The value of specific yield selected (10%) can be regarded as conservative and actual values may well be higher, possibly up to 25% or more. Such values do commonly occur in unconsolidated uniform sands of medium grain size. No values of specific yield could be determined during the pumping tests on account of the site conditions. In practice, specific yield is likely to vary in space on account of the varying lithology of the saturated formations. The variations are three dimensional, giving in effect a time variation also, in view of the changes in water levels which will occur following abstraction. It should be noted that recharge to the entire aquifer systems is held not to occur other than by laterial inflow from within the aquifers, and the existing gradients are regarded as transient semi-steady state configurations. Since the P.M.M. aquifer only is under consideration, leakage from a lower or laterally located aquifer may occur in principle and could modify the predicted drawdowns.

In considering the predicted contours of drawdowns and water levels at various time intervals, it should be remembered that these are based on average values of water level over the grid areas and not pumping well drawdowns. The values may or may not be realistic depending on the accuracy of the input data and the boundary conditions and a significant factor may well be the extent and continuity of the clay layers within the aquifer to which no consideration has yet been given.

Assuming for the present that the predicted water level changes are correct, the pumping well drawdowns will need also to take account of the specific capacities of the producing wells. Observed specific capacities in the test wells have been measured during development pumping or at an early stage during the main pump test. For a similar design of well, specific capacities will be modified in future by:-

a. the reducing transmissibility consequent upon drawdown of the water table

b. the well losses which will tend to increase if production is maintained, although these could be decreased by other factors, such as improved development.

c. the longer-term changes in boundary conditions.

The longer-term changes in boundary conditions are also most likely to be related to the effect of clay layers but in this instance a localised occurrence could be significant. Initial drawdowns have followed a trend consistent with leaky artesian conditions with little or no drawdown occurring in the overlying layer(s) above the leaky horizon. This condition will obviously change with time. The overall effect will be difficult to predict without information on the extent and continuity of the clay layers and on the anisotropy characteristics of the overlying layers but in any event the trend will be towards reductions in the specific capacity.

One further aspect can be mentioned here. If the amount of pumping drawdown is likely to be a significant factor in the proposed development field, improvements of specific capacity are possible by modifications of well design. Screens could be extended over all or the greater part of the aquifer to gain the advantage of water table conditions and reduce vertical flow effects. It will be necessary in those circumstances to install the pump in the screen which is likely to increase corrosion effects and the likelihood of mechanical damage but design modifications could be incorporated to offset these effects.

2.7.2.1. Development Scheme 'A'

Node	Abstraction (m^3/day)
(24.19)	41000
(24.20)	41000
(25.19)	41000
(25.20)	41000
(28.19)	41000
(28.20)	41000
(29.19)	41000
(29.20)	41000
Total	328000 m^3/day

This regime represents pumping from 8 groups of 6 wells in two areas [Map Figure 14c] and corresponds to 48 wells each pumping at 1250 U.S. gals/minute. The two areas are 9 km square with centres located 18 km apart.

In these areas the initial saturated thickness of the aquifer is 80-100 metres and the initial transmissibility is 800-1000 m^2/day. The non-steady state finite difference equations were set up for each node using an initial time increment of 1 month which was increased progressively by about 20% for each further increment. The equations were solved by an alternating direction technique yielding values of water levels at each node after each time increment. Account was taken of the decrease in transmissibility due to drawdown of the water table with time. The computation was terminated when the water table reached the base of the aquifer. The water levels and regional drawdowns after 10 years and 25 years are shown in Map Figures 10c-13c.

The abstraction regime corresponds to a fairly high well density with high-production wells. It is apparent that drawdowns of the water table are considerable in areas where the pumping is concentrated. Allowing for reduced specific capacity and the same well design, pumping drawdowns could reach present screen levels before 10 years have elapsed. The cone of depression after 25 years is approaching the western boundary of the aquifer and the effects are hard to predict. Variable boundary conditions have been incorporated in the model but in the south increasing leakage is probable in consequence of increased head differentials. The effects of lateral movement from the zones of poor quality water to north and east are unlikely to be significant.

2.7.2.2. Development Scheme 'B'

This scheme was as follows:- 33 abstraction wells [Map Figure 19c] each pumping 1070 U.S. gals/minute (4636 m^3/day) and spaced in 3 equal rows. The spacing between rows was 12 km and between wells was 4 km. The total production was therefore 152 000 m^3/ day. This is equivalent to the proposed requirements for the Agedabia supply from the Phase 1 Area estimated at 85% of a producing rate of 180 000 m^3/day. Required pumping rates for 33 wells would be 1260 U.S. galls/minute.

The well field is spaced over an area of 800 sq km in the main central area of good quality water in the P.M.M. aquifer, and predictions have been prepared for periods up to 100 years. The results suggest that with this rate of pumping and allowing for reduced specific capacity, the rate could be sustained for 50 years, possibly without pumping drawdowns attaining present screen level except in the central areas. Some modification to improve specific capacity seems desirable. It is unlikely that significant deterioration of water quality will occur under these conditions.

2.7.2.3. Conclusions

Two development schemes have been applied to the aquifer model, one a high density well field at a production rate of 328 000 m^3/day which results in excessive drawdowns after relatively short periods of time; and a second in a more widely-spaced field producing at a rate of 153 000 m^3/day, for which predicted results appear practicable.

It should be emphasised that the estimates of drawdown are provisional and should be regarded with caution. There are a number of uncertainties, notably the assumed value of specific yield and the possible influence of the intermediate clay layers. The value of 10% for the assumed specific yield is probably conservative and actual values are likely to be higher. The effect of the clay layers may cause leaky artesian conditions to persist which will affect predicted drawdowns. Modifications of well design to offset this effect and incidentally also to improve specific capacity may be desirable. Consideration can perhaps be deferred until more refined predictions can be presented in the final report.

Studies are currently in progress on various aspects which include:-

1. A development scheme for local irrigation in the Phase 1 Area at a production rate of 100 000 m^3/day with a 10% annual production requirement. Well fields to irrigate 10 000 hectares will be sited in two blocks 17 by 3 km and predictions will be directed to obtain:-

   a. the period for drawdowns to attain screen level for current design

   b. the period and location for which water can be conveniently piped into the two areas from outside.

2. Considerations of leaky artesian effects with drawdowns occurring in the overlying aquifer - by model and analysis.

3. Correlation of the detailed lithological chaaracteristics with computed permeabilities by analysis and by pumping test data.

4. Consideration of water quality changes which may occur during proposed pumping regimes.

3. SUMMARY AND CONCLUSIONS

3.1 AQUIFERS: GENERAL OCCURRENCE

(i) Two aquifer systems have been recognised in the Phase 1 Area:- the Post-Middle Miocene and the Miocene/Oligocene. On a regional scale, the former can be considered as one aquifer; the latter is a multi-aquifer system. [Map Figure 5].

(ii) The P.M.M. aquifer extends over the eastern two-thirds of the Phase 1 Area. Under steady-state, natural flow conditions, it occurs essentially unconfined. The water table contours strike east-west with a low gradient between 1:10 000 and 1:20 000 to the north. [Map Figure 9].

(iii) The Miocene/Oligocene aquifer system outcrops in the western third of the Phase 1 Area with the water table occurring mainly in the Miocene Formations but eventually - on account of the easterly dip - within the Oligocene in the extreme south-west. The Miocene/Oligocene system exists fully confined below the P.M.M. aquifer outcrop. [Map Figure 9 and Map Figure 5].

(iv) Hydraulic head in the Miocene/Oligocene system is generally higher than in the P.M.M. aquifer. In the central Phase 1 Area adjacent to the outcrop boundary, a maximum difference of 150 feet is apparent [Map Figure 9] decreasing southwards to eventual continuity. Maximum head differentials of 115/145 feet occur between the deep Oligocene and the P.M.M. aquifer in the Occidental 103 D and A field areas respectively. [Table 5].

(v) Leakage upwards into the P.M.M. aquifer does not seem to occur in the central and northern Phase 1 areas due to the presence of clay horizons in the boundary formations. Leakage is more likely to occur farther south where a head differential still exists and where the boundary formations include more permeable material. Leakage in the eastern Phase 1 Area may occur and there are some indications of this but geochemical trends do not confirm.

(vi) Current recharge to the entire post-Eocene aquifer systems in the Phase 1 Area does not appear to occur other than by lateral inflow from within the aquifers from regions to the south. The current gradient is regarded as probably transient with lateral inflow being exceeded by discharge in the sabkhats to the south of the Sirte Gulf. The assertion is based on regional consideration and lacks factual proof. Carbon-14 age dating for the P.M.M. groundwater gives a range between 10 000 and 34 000 years plus.

3.2 POST-MIDDLE MIOCENE AQUIFER

(i) To the south of latitude 29° N, the P.M.M. aquifer is mostly developed in the Calanscio Formation composed of uniform, medium with some fine or coarse, unconsolidated sand with subordinate clay interbeds; to the north of this latitude, it occurs mostly in a lower unit [Aklash Formation] of clayey sands and sandstones, with clays and limestones.

(ii) Saturated thickness is in the main range of 260-430 feet increasing generally eastwards. Maximum thickness in excess of 590 feet occurs on the eastern margin of the Phase 1 Area. [Map Figure 7c].

(iii) Depth to the water table varies from 300 feet plus in the central Phase 1 Area decreasing to the north, south and east, with minimum values of a few feet in the vicinity of Jalu oasis. [Map Figures 2 and 9].

(iv) Although the P.M.M. aquifer occurs unconfined in steady-state natural flow conditions, during short duration pumping tests [5-10 days] with screened lower half or two-thirds, it behaves like a multiple body with leaky artesian lower layer(s) and an unconfined surface layer.

(v) The steady-state, natural flow occurrence with common water table and piezometric surface, i.e. no vertical flow component, suggests that the clay layers, which cause development of leaky artesian conditions are discontinuous and that in the long term, the aquifer will react to abstraction as an effectively unconfined body with corresponding specific yield.

(iv) Lateral permeability values [8 reliable results only considered] for the upper sands (Calanscio Formation) derived by pump testings were in the range 9 to 23 m/day with an average value of 14 m/day. [Table 6]. The permeability of the lower (Aklash) formation is likely to be less.

(vii) Pump test results extrapolated to estimate transmissibility at the eight locations show a range between 627 and 1152 m^2/day with average value of 1100 m^2/day [88 000 U.S. galls/day/ft]. [Table 6].

(viii) Values of storage coefficient determined during pump tests were all in artesian range [average value = 5.3×10^{-4}]. For water resources model calculations, a value of 10% has been provisionally chosen as a conservative estimate but true values could easily attain 25%.

(ix) Distribution of regional transmissibility values determined by model studies are slightly lower than local values based on pumping tests for individual interpolated positions. Average value for same locations as in (vii) based on interpolated contours equals 884 m^2/day [20% lower].

(x) Computer derived values of transmissibility suggest an order of 500 to 100 m^2/day for the central and southern Phase 1 Area increasing to 1500 m^2/day in the north and 2000 m^2/day in the east. [Map Figure 7c]. Increase correlates with thickness increases despite probably lower permeability indicated by lithology. No pumping tests have been carried out in these marginal areas.

3.3 MIOCENE/OLIGOCENE AQUIFER SYSTEM

3.3.1. Miocene Aquifers

(i) These are developed in Lower and Middle Miocene Formations which include carbonates, sands and sandstones, and clays. Lithofacies studies limited to upper 500 feet show the occurrence of three NW-SE trending belts with details as follows:-

NE Belt:	limestones, dolomites and interbedded clays.
Centre Belt:	sands, sandstones, limestones and clays. [gypsum/anhydrite developed in NE belt and parts of centre].
SW Belt:	sands, sandstones and clays with subordinate limestones.

(ii) Saturated thickness in the central Phase 1 Area is in the order of 1000 feet increasing to 1500 feet in the north (Amal Field). Saturated thickness reduces progressively westwards in consequence of easterly dip and unconfined conditions. Depth to water table ranges from zero around the Hutaytat al Fawziyah sabkhat to 550 feet in the south-west corner. [Map Figures 2 and 9].

(iii) No pumping tests have been carried out in the Miocene aquifers but lithological variations would indicate higher permeabilities in formations in the south-west belt.

3.3.2. Oligocene Aquifers

(i) The Oligocene formations include mainly sands, sandstones and shale and generally subordinate carbonates. Shale content increases from south to north. Saturated thickness is the order of 1000 feet in the southern Phase 1 Area increasing to perhaps double this in the north. Unconfined conditions limited to south-west corner with water table at 300 feet approximately below ground level.

(ii) No pumping tests have been carried out in the Oligocene aquifers but the higher sand content in the southern areas would indicate higher permeabilities.

3.4 GROUNDWATER QUALITY

3.4.1. Miocene/Oligocene Aquifer Systems

(i) Information on near-surface outcrop section of Miocene aquifer shows total mineralisation along boundary of P. M. M. aquifer may be 1000 mg/l or less, increasing westwards to 3000 mg/l. Changes probably relate to aquifer lithology. [Map Figure 11].

(ii) Deep wells within the Oligocene aquifer in the central and eastern Phase 1 Area [Occidental A and D Fields, and Gialo Field], produce water of very variable quality including highly mineralised as well as some of moderate degree (5000 mg/l).

(iii) Shallow wells in Oligocene formations in south-west corner show mineralisation in excess of 3000 mg/l. [Map Figure 10]. Information elsewhere in the Phase 1 Area is lacking but in a deep well drilled recently at Q1-65 immediately south of the Phase 1 boundary on longitude 21°E, water in the Oligocene rocks had SEC lower than 3000 micromhos, indicating total mineralisation of probably less than 2000 mg/l.

3.4.2. Post-Middle Miocene Aquifer

(i) There is a central lobe in the Phase 1 Area with groundwater of mineralisation 1000-2000 mg/l, higher values occurring to the north with change from south generally progressive. Compositions generally constant in vertical plane.

(ii) Mineralisation increases rapidly and progressively north of 29° 20' N to values in excess of 6000 + mg/l. Changes can probably be correlated with lithology.

(iii) Mineralisation also increases to east but relations are more complex with alternating north-trending zones of fresh and poor quality water. Regional values exceed 6000 mg/l with local higher values which in some instances may have resulted from current evapotranspiration concentrations. Regional increases may relate to lithological changes in the P. M. M. aquifer but correlation is not clear. Geochemical analysis does not support concept of leakage from deeper Miocene aquifers but factual evidence limited.

3.5 WATER RESOURCES

3.5.1. Oligocene/Miocene Aquifers

(i) No detailed studies have been made of these aquifers and only general indications of potential can be provided based on the limited data available.

(ii) Water quality in the shallow Miocene formations is moderate (1000-3000 mg/l) in the western outcrop area and in the southerly confined extension. On the basis of lithology, aquifer transmissibility is likely to be higher in the south to south-western Phase 1 Area where sand percentage in the formations is significant. Water quality in the deeper formations in the southern Phase 1 Area may well be of comparable quality (2000-3000 mg/l) but no testing has been carried out other than at Q1-65 south of the southern Phase 1 boundary line. Development in this area would require to be preceeded by test drilling but could be considered in conjunction with development of the P. M. M. aquifer.

(iii) Because of lithological changes in the Miocene formations to the north and east with increasing carbonate and shale percentage, both water quality and permeability of aquifer is likely to decrease.

(iv) The deeper Oligocene aquifer seems unlikely to contain water of tolerable quality except possibly in the southern Phase 1 Area. [Q1-65 test hole]. Quality and permeability is likely to decrease northwards concomitant with increasing shale content in the aquifer formations and also because of the absence of discharge locations reducing flow through. Water quality is known to be variable in deep wells in Occidental A and D, Gialo and Nafoora fields and although some is of moderate quality (around 5000 mg/l), adequate testing for resources evaluation would require fairly extensive and costly drilling.

3.5.2. Post-Middle Miocene Aquifer

(i) Water resources evaluation in terms of predictive well field development has been carried out using a computer model.

(ii) The well fields selected occur in the zone of good quality water (less than 2000 mg/l) and additional factors taken into consideration have included the thickness of the aquifer, nearness to sources of power and centres of population, and distance from the aquifer's boundary and from locations with poor quality water.

(iii) Assumed boundary conditions are vertical uniformity and plane horizontal anisotropy (variable transmissibility) in a single unconfined aquifer with specific yield of 10%.

(iv) Regional assumption of unconfined conditions and 10% specific yield in unsteady-state computer model drawdown calculations, assumes no significant effect from clay layers in the long term. Coincidence of water table and piezometric surface under present natural flow conditions is regarded as confirmatory evidence that clay layers are effectively discontinuous.

(v) Development scheme 'A' which models a high density well field producing 380 000 m^3/day, results in excessive drawdowns in short periods of time.

(vi) Development scheme B is of a widely spaced field producing at a rate of 153 000 m^3/day - required for piping to Agedabia, - and predicted results appear practicable with a regional drawdown after 50 years of between 10 and 20 metres over the well field area.

(vii) Caution is emphasised in considering the results due to the uncertainty in the various assumptions. The main factor which is likely to increase drawdowns if assumptions incorrect is the effect of the clay layers, but this may be offset by modifications to well design to improve specific capacity.

(viii) Deterioration of water quality by lateral inflow of poor quality water from areas to east or north is not anticipated during the periods modelled. Deterioration of water quality by vertical leakage from deeper aquifers is also not anticipated. The P. M. M. aquifer normally shows a well-defined basal clay layer in the proposed well-field areas. Additionally, the immediately underlying Lower and Middle Miocene formations are also clay-rich in this area. To the south a lithological change to more permeable formations in the upper L. M. M. does occur but in that area, water quality in the shallow Miocene aquifer is likely to be comparable to that in the P. M. M. aquifer.

(ix) Confirmatory evidence that quality deterioration is unlikely to occur by upconing is that no deterioration occurred during the periods of the pumping tests. Additionally, the water wells which have been producing from the Occidental A and D field areas at quite high production for several years show a quality comparable with the general quality of the P. M. M. aquifer groundwater in the same area.

3.6 WELL DESIGN

(i) A screen diameter of 8 inches is adequate for the required production rates if a length of screen in excess of 100 feet is used.

(ii) Increasing screen length upwards may be a worthwhile consideration in order to improve specific capacity - by changing flow conditions from leaky artesian to unconfined. Increase would need to be correlated with position of clay layers at particular sites. Increase would also imply need to install the pump inside the screen which would require a larger-diameter screen (10 inches minimum) in order to contain the pump bowl, but this increased diameter could be limited to the upper section. To avoid mechanical damage to screen, a strengthened section of screen or blank casing could be installed opposite the pump bowl.

(iii) Reducing screen length downwards (partial penetration) may also be considered to reduce costs whilst still maintaining sufficient production rate with insignificant head loss increase. There is some theoretical justification for this possibility which is being currently studied. Most reliable procedure recommended to test effects of both (ii) and (iii) would be a test well incorporating such features and capable of being tested during production by down-hole flow meter.

(iv) Screen Type: a form of slotted screen with gravel pack is recommended. Slot size should retain 85-90% of an emplaced gravel pack but coarser slots can be used with a pre-pack filter type. With an emplaced gravel pack a screen slot size of .020-.030 inches is likely to be required on account of the uniform grain size of the aquifer and an assumed pack-aquifer ratio of less than 10. Maximum open area is desirable, preferably not less than 15%. In view of the relatively high mineralisation of the well waters, some non-corrosive material such as fibre-glass, stainless steel or rubber-coated steel is desirable.

(v) Gravel Pack: a pack thickness not exceeding three inches is recommended in order to assist demudding and well development. A pack-aquifer ratio of less than 8 for a uniform pack, or less than 10 for a graded pack, should give adequate security against sand pumping. Uniform packs are to be recommended on account of ease of emplacement. A pre-pack filter has also considerable advantages in this respect and results to date have shown moderate to good well efficiencies. [Table 6]. Possible disadvantages in long-term use may relate to removal of encrustation within pack, and manufacturers assurances with confirmatory data should be sought if this pack type is proposed for use.

(vi) Casing: Published literature tends to recommend a 14 inch to 16 inch OD casing for a production rate of 850-1300 gpm in order to keep well losses small. It should be noted that for a test well permitting the use of a down-hole flow meter, adequate clearance of the pump bowl is required. With the equipment at present available, 16 inch casing in a minimum diameter and even with this size, testing is difficult.

(vii) Drilling: rotary or reverse rotary drilling is recommended with good provision made to collect samples for lithological analysis. For initial test wells, the type of rig referred to as 'Con-Cor' would seem to have considerable advantages. For rotary drilling, the use of Revert drilling mud would materially assist well development. The use of a bentonite mud is not recommended for this aquifer unless improved control than hitherto attained can be assured.

(viii) Site Selection: it is recommended that test drilling should be carried out at any proposed new well field in order to ascertain the local lithological nature of the boundary conditions and to ensure that vertical leakage of poor quality water from below is unlikely to occur.

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TABLE 1a

Sand size ranges and descriptions used in text - after Wentworth

Microns	inches (thousandths)	Description
63-125	2.5 - 5	Very fine sand
125-150	5 - 10	Fine sand
250-500	10 - 20	Medium sand
5000-1mm	20 - 40	Coarse sand
1mm-2mm	40 - 80	Very coarse sand
(Above 2mm)		(gravel)

TABLE 1b

Sieve sizes used in sand and gravel analysis

Microns	inches	∅ Phi
63	0.00248	4.0
90	0.00354	~3.5
125	0.00492	3.0
180	0.00709	~2.25
250	0.00984	2.0
355	0.01398	~1.5
500	0.01969	1.0
710	0.02795	0.5
1000	0.03937	0.0
1400	0.05512	~-0.5
2000	0.07874	-1.0
2800	0.11024	~-1.5
4000	0.15748	-2.0
5600	0.22047	~-2.5
8000	0.31496	-3.0

TABLE 2

Details of screened interval and gravel packs in Exploration/Production wells. [D_{50} and D_{90} sizes in microns; uniformity coefficients = D_{40}/D_{90}].

INTERVAL [feet below ground level]	AQUIFER D_{50} Average	AQUIFER D_{50} Range	AQUIFER D_{90} Average	AQUIFER D_{90} Range	Uniformity Coefficient Average	Uniformity Coefficient Range	PACK Pack Aquifer Ratio Average	PACK Pack Aquifer Ratio Range	PACK Unif. Coeff.	Type (size range in mm)
JA										
300-340	386	320-470	163	135-178	2.8	2.3-3.2	-	-	conforms	casing
340-450	306	210-350	138	105-200	2.7	2.1-3.4	9.8	8.6-14.3	to aquifer	graded emplaced
445-505	210	142-275	90	75-120	2.8	2.2-3.9	8.8	6.7-13.0		graded emplaced
JB										
370-437	311	300-330	120	95-142	2.8	2.5-3.3	7.7	7.2- 8.0	conforms	graded emplaced
437-491	251	195-310	108	95-123	2.8	2.4-3.0	8.0	6.5-10.2	to aquifer	graded emplaced
491-573	182	160-225	108	94-125	2.0	1.8-2.3	6.9	5.6- 7.9		graded emplaced
JC										
302-350	340	265-460	177	100-263	2.3	1.6-3.4	-	-	conforms	casing
350-410	328	245-395	175	130-214	2.0	1.6-2.4	9.0	7.6-12.0	to aquifer	graded emplaced
410-450	236	200-310	110	90-160	2.5	1.6-2.7	8.4	6.5-10.0		graded emplaced
450-501	325	260-400	163	130-163	2.3	2.0-2.8	9.2	7.5-11.5		graded emplaced
JD										
240-330	436	360-560	219	180-275	2.5	2.0-3.0	-	-	-	casing
330-410	320	235-350	161	130-185	2.4	2.1-2.7	4.6	4.2- 6.3	less than 2	uniform pre-pack (1-2)
410-470	427	365-460	210	170-245	2.3	2.0-2.7	5.6	5.4- 6.8	less than 2	uniform pre-pack (2-3)
470-500	353	320-380	161	145-175	-	-	4.2	3.9- 4.7	less than 2	uniform pre-pack (1-2)
JE										
270-360	366	265-460	177	125-210	2.5	2.1-2.7	-	-	-	casing
360-450	382	370-450	175	145-210	2.5	2.2-2.7	6.5	5.6- 6.8	less than 2	uniform pre-pack (2-3)
450-520	321	240-390	147	118-185	2.6	2.3-2.8	4.7	3.8- 6.2	less than 2	uniform pre-pack (1-2)
JF										
240-350	418	300-540	197	155-250	2.4	2.1-3.0	-	-	-	casing
350-460	318	270-390	179	130-205	2.1	2.0-2.3	4.7	3.8- 5.6	less than 2	uniform pre-pack (1-2)
460-510	275	225-330	148	115-180	2.1	1.9-2.2	3.5	2.9- 4.2	less than 2	uniform pre-pack (0.7-1.2)

TABLE 3

Data on Hagusta pre-pack gravel filters

pack size range (mm)	flow speed through pack (cm/sec)	particle size passing (microns)	particle size retained	permeability in litres/sec/m^2 at 100 cm pressure	pore sizes[1] (microns)
0.7-1.2	4.6	60	150	50	285
1.0-2.0	11.3	150	300	120	450
2.0-3.0	15.1	300	500	190	750

[1] Calculated assuming single size particles equivalent to median size and 40% porosity.

TABLE 4

Post-Eocene sediments, Phase 1 Area

			Approx. thickness in feet
Recent	—	Surface sands, gravels and calcrete	?
Post-Middle Miocene	Calanscio Formation	Medium, with some fine or coarse sands, grading to calcareous sandstones in part, with thin clay interbeds.	500
Post-Middle Miocene	Aklash Formation	Generally clayey sandstones and sands, clays, occasional fossiliferous limestones in the north.	1000 (Aklash and Marada Formations together)
Lower and Middle Miocene	Marada Formation	Predominantly limestones and clays, with evaporites. Interbedded sands and sandstones occur to the south-west.	
Oligocene	Diba Formation	Fine to coarse, commonly glauconitic sandstones with occasional interbedded shales.	1000 (Diba and Arida Formations together)
Oligocene	Arida Formation	Fine glauconitic sandstones with interbedded shales below, thick shale above.	

TABLE 5

Data from wells within the Oligocene at Occidental's 103 'A' and 'D' Fields and the Gialo Field [Oasis, 59]. Measurements of static level and conductance made in 1972 unless otherwise stated. General ground elevation at 'A' Field is 325 feet above mean sea level, at D Field, 343 feet and at Gialo Field 319 feet.

	Perforated interval in feet below ground level	Static water level ft a.m.s.l.	Specific electrical conductance in micromhos/cm at 25°C	Type of sample and Well Status at time of measurements
103 A				
W.S.W. 2	? - 2946	-	9,550	Pumping
W.S.W. 4	? - 2928	-	6,600	Pumping
W.S.W. 20	2790 - 2918	122	6,350	Depth sample, Standing Idle (S.I.)
W.S.W. 21	2660 - 2924	-	6,500	Pumping
W.S.W. 22	2861 - 2924	193	-	S.I.
W.S.W. 23	2827 - 2942	-	10,800	Pumping
W.S.W. 27	2808 - 2969	88	-	S.I.
W.S.W. 30	3524 - 3705	82	-	S.I.
W.S.W. 30	" "	"	30,000 approx.	Depth sample in casing at 400 feet b.g.l.
W.S.W. 30	" "	"	68,000 approx.	Depth sample in casing at 450 feet b.g.l.
W.S.W. 31	3525 - 3645	99	-	S.I.
W.S.W. 31	" "	"	7,000	Depth sample in casing at 250 feet b.g.l.
W.S.W. 31	" "	"	68,000	Depth sample in casing at 265 feet b.g.l.
W.S.W. 34	? -	198	6,850	S.I. Depth sample in casing at water level
W.S.W. 36	2367 - 2908	-	5,850	Pumping
W.S.W. 38	2292 - 2711	217	-	S.I.
W.W. 19	2699 - 2761	253 (Dec 1967)	8,500 (on compl)	Pumping
W.W. 20	2851 - 2950	251 (Dec 1967)	11,880 (on compl)	Pumping
W.W. 67	? - 2790	179	-	S.I.
103 D				
W.S.W. 6	? - 2977	141	-	S.I.
W.S.W. 7	2820 - 2955	-	15,000	Pumping
W.S.W. 8	2800 - 2912	-	18,000	Depth sample in casing at water level
W.S.W. 9	2800 - 2981	151	-	S.I.
W.S.W. 10	2977 - 2983	-	18,250	Pumping
W.S.W. 13	2656 - 3461	-	6,500	Pumping
W.S.W. 14	3487 - 3518	215	-	S.I.
W.S.W. 15	?	-	18,000	Depth sample in casing
W.S.W. 16	3437 - 3729		8,100	Pumping
W.S.W. 18	2251 - 2935		6,800	Pumping
W.S.W. 51	2200 - 2940		7,050	Pumping
W.W. 37	1946 - 2071	-	9,750	Pumping
W.W. 38	1830 - 1945	-	6,100	Pumping
W.W. 230	1786 - 1963		7,400	Pumping
W.W. 234	?		7,400	Pumping

TABLE 6

Aquifer characteristics based on observed and extrapolated pumping test results

Site	rt ft m	rte ft m	T USg/d/ft m^2/day	% M.D.	K USg/d/ft^2 m/day	S x 10^{-4}	S.C. gpm/ft l/sec/in	Eff %	ut ft m	ute ft m	tte ft m	Te	st ft m	Ka (units see K)	COMMENTS M.D. = Mean Deviation
JB	115	110	48,634	11	442	2.6	17.9	87	130	100	210	92,759	245	378	
	35.1	33.5	604		18.0		3.7		39.6	30.5	64.0	1,152	74.7	15.4	
JC	265	230	131,167	8	569	6.1	24.6	44	-	-	230	131,167	265	493	
	30.8	70.1	1629		23.2		5.1		-	-	70.1	1629	80.8	20.1	
JD	250	225	50,325	23	223	7.6	22.7	81	40	30	255	56,936	290	196	
	76.2	68.6	625		9.1		4.1		12.2	9.1	77.7	707	88.3	8.0	
JE	148	130	37,683	13	290	4.8	14.0	67	95	85	215	62,242	243	255	T values not based on analysis of JE-01 and JE-02 measurements
	45.1	39.6	468		11.8		2.9		29.0	25.9	65.5	773	74.1	10.4	
JF	171	161	36,073	10	223	3.6	12.1	70	75	65	226	50,487	246	206	
	52.1	49.1	448		9.1		2.5		22.9	19.8	68.9	627	75.0	8.4	
J(KK1-12)	165	145	64,093	0	442	5.5	-	-	115	60	205	90,585	378	240	air-lift test
	50.3	44.2	796		18.0		-		35.1	18.3	62.5	1125	115.2	9.8	
J(F1-97)	150	125	34,221	12	275	6.9	-	-	156	136	261	73,675	306	240	air-lift test
	45.7	38.1	425		11.2		-		47.5	41.5	79.5	915	93.3	9.8	
J(C1-95)	176	151	47,829	-	317	-	-		450	130	281	88,894	926	96	air-lift test
	53.6	46.0	594		12.9		-		137.1	39.6	85.6	1104	282.2	3.9	
J(A1-LP5C)	-	-	-	-	-	-	-								Air lift test on Miocene aquifer. Results shown based on K estimated from lithology.
	-	-	-		-	-	-		56	41	41	410	56	7.3	

N.B. No data has been provided on the following sites:

1. JA - results of pumping test not suitable for valid analysis (see Appendix 1)

TABLE 7

Comparison of transmissibility (m^2/day) values at test drilling locations. [Column 1 = 'model' and Column 2 = extrapolated pumping test results].

Site	Nearest Node	1	2
JB	(22, 17)	607	1152
JC	(27, 20)	950	1629
JD	(27, 24)	930	707
JE	(19, 21)	530	773
JF	(19, 25)	615	627
J(KK1-12)	(24, 27)	785	1125
J(F1-97)	(30, 23)	1260	915
J(A1-LP5C)	(21, 15)	430	410
J(C1-95)	(18, 38)	1400	1104

TABLE 8 Field chemical analyses and derived parameters per groundwaters sampled during the Phase I test pumping and associated sampling. Corrater readings where indicated and included in the Appendices

Well identity	JAP	JAP	JAP	JBP	JBP	JCP	JCP	JCP	JDP	JDP	JDP	JEP	JEP	JEP
IGS reference	73/174	73/175	73/176	72/277	72/278	72/505	72/506	72/507	72/609	72/610	72/611	73/121	73/122	73/123
Date of analysis	9.3.73	11.3.73	13.3.73	3.7.72	5.7.72	4.10.72	8.10.72	13.10.72	25.11.72	28.11.72	2.12.72	27.12.72	30.12.72	4.1.73
Aquifer	PMM	PMM	PMM	PMM	PMM	PMM	PMM	PMM	PMM	PMM	PMM	PMM	PMM	PMM
Formation temp. (°C)	26.0	26.0	26.0	27.2	27.0	28.3	28.3	28.4	–	–	28.0	27.5	27.5	27.5
Field pH	7.60	7.70	7.65	7.46	7.20	7.68	7.86	7.98	7.23	7.38	7.41	7.96	7.91	7.67
Field HCO_3 (mg/l)	254	267	254	257	259	168	174	174	188	184	186	218	191	192
Free CO_2 (")	10.0	8.4	9.0	14.0	25.0	5.5	3.8	2.8	–	–	11.0	8.7	3.7	6.5
K_{IAP} (calcite)	$5.6x10^{-7}$	$7.5x10^{-7}$	$6.9x10^{-7}$	$3.4x10^{-7}$	$1.9x10^{-7}$	$5.4x10^{-7}$	$8.6x10^{-7}$	$1.1x10^{-6}$	–	–	$4.2x10^{-7}$	$5.9x10^{-7}$	$1.0x10^{-6}$	$6.5x10^{-7}$
$K_{CALCITE}$	$3.9x10^{-7}$	$3.9x10^{-7}$	$3.9x10^{-7}$	$3.8x10^{-7}$	$3.8x10^{-7}$	$3.6x10^{-8}$	$3.6x10^{-8}$	$3.6x10^{-8}$	–	–	$3.6x10^{-7}$	$3.7x10^{-7}$	$3.7x10^{-7}$	$3.7x10^{-7}$
Calcite Saturation (%)	140	190	170	90	50	140	230	300	–	–	110	150	290	170
K_{IAP} (dolomite)	$2.8x10^{-15}$	$5.1x10^{-15}$	$4.0x10^{-15}$	$1.0x10^{-15}$	$3.1x10^{-17}$	$2.2x10^{-15}$	$5.7x10^{-15}$	$1.0x10^{-14}$	–	–	$1.2x10^{-15}$	$3.0x10^{-15}$	$1.0x10^{-14}$	$3.4x10^{-15}$
Specific elect. Cond.	2180	2110	2160	–	–	–	–	–	–	–	–	2650	2620	2730
eH (mv)	+216	+205	+186	–	+195	–30	–8	–15	+109	+197	+194	+79	–	+179
Corrater readings	–	–	✓	–	✓	–	–	✓	–	–	✓	–	–	✓

Well identity	JFP	JFP	JFP	S1-103 (JA)	W36-103A	W37-103A	W81-103A	W80-103D	W79-103D	W51-103D	W52-103D
IGS reference	73/163	73/164	73/165	73/262	72/270	72/271	73/189	73/190	73/191	72/265	72/267
Date of analysis	14.2.73	17.2.73	22.2.73	6.2.73	5.4.72	5.4.72	6.4.72	4.4.72	4.4.72	13.4.72	13.4.72
Aquifer	PMM	PMM	PMM	PMM	M/OLIG	PMM	PMM	PMM	PMM	M/OLIG	PMM
Formation temp (°C)	28.5	28.0	28.0	28.0	47.2	27.5	27.8	27.5	26.8	46.5	28.0
Field pH	7.62	7.43	7.42	–	6.93	7.31	7.33	7.38	7.33	7.06	7.29
Field HCO_3 (mg/l)	230	229	227	–	173	205	195	205	235	166	235
Free CO_2	8.8	13.0	13.0	–	32	13	14	13	17	18	11
K_{IAP} (calcite)	$7.5x10^{-7}$	$4.7x10^{-7}$	$3.9x10^{-7}$	–	$2.2x10^{-7}$	$2.9x10^{-7}$	$3.3x10^{-7}$	$4.1x10^{-7}$	$4.1x10^{-7}$	$2.0x10^{-7}$	$2.1x10^{-7}$
$K_{CALCITE}$	$3.6x10^{-7}$	$3.6x10^{-7}$	$3.6x10^{-7}$	–	$2.1x10^{-7}$	$3.7x10^{-7}$	$3.7x10^{-7}$	$3.7x10^{-7}$	$3.8x10^{-7}$	$2.1x10^{-7}$	$3.6x10^{-7}$
Calcite Saturation (%)	200	120	100	–	100	79	89	110	100	96	57
K_{IAP} (dolomite)	$4.8x10^{-15}$	$1.8x10^{-15}$	$1.5x10^{-15}$	–	$2.3x10^{-16}$	$6.6x10^{-16}$	$8.2x10^{-16}$	$1.2x10^{-15}$	$1.7x10^{-15}$	$1.7x10^{-16}$	$3.3x10^{-16}$
Specific elect. Cond.	2630	2690	2660	–	–	–	–	–	–	–	–
eH (mv)	+132	+144	+144	+204	–94	+180	+377	+280	+245	–25	+167
Corrater readings	–	–	✓	–	–	–	–	–	–	–	–

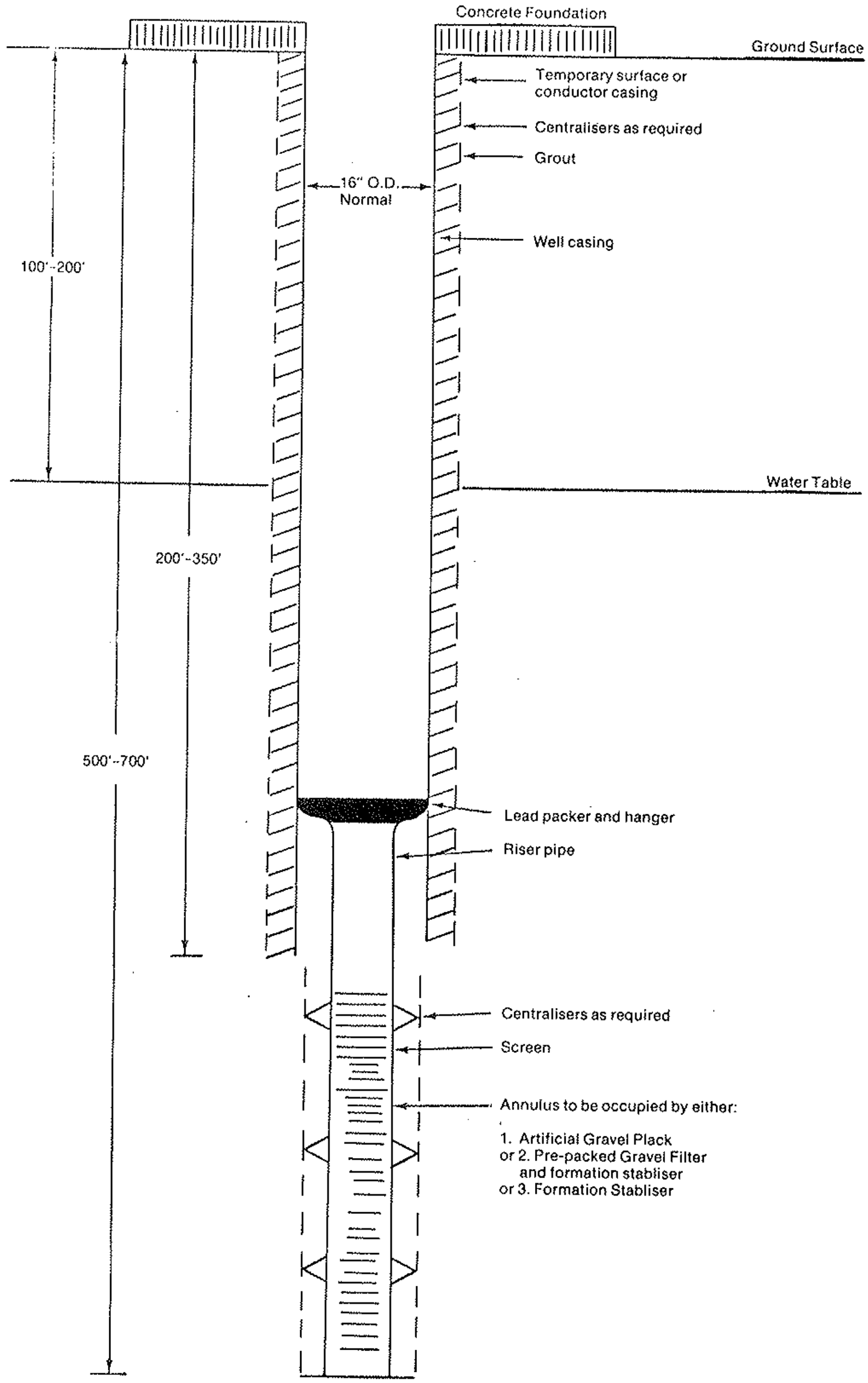

Fig. 1. Exploration/Production Well

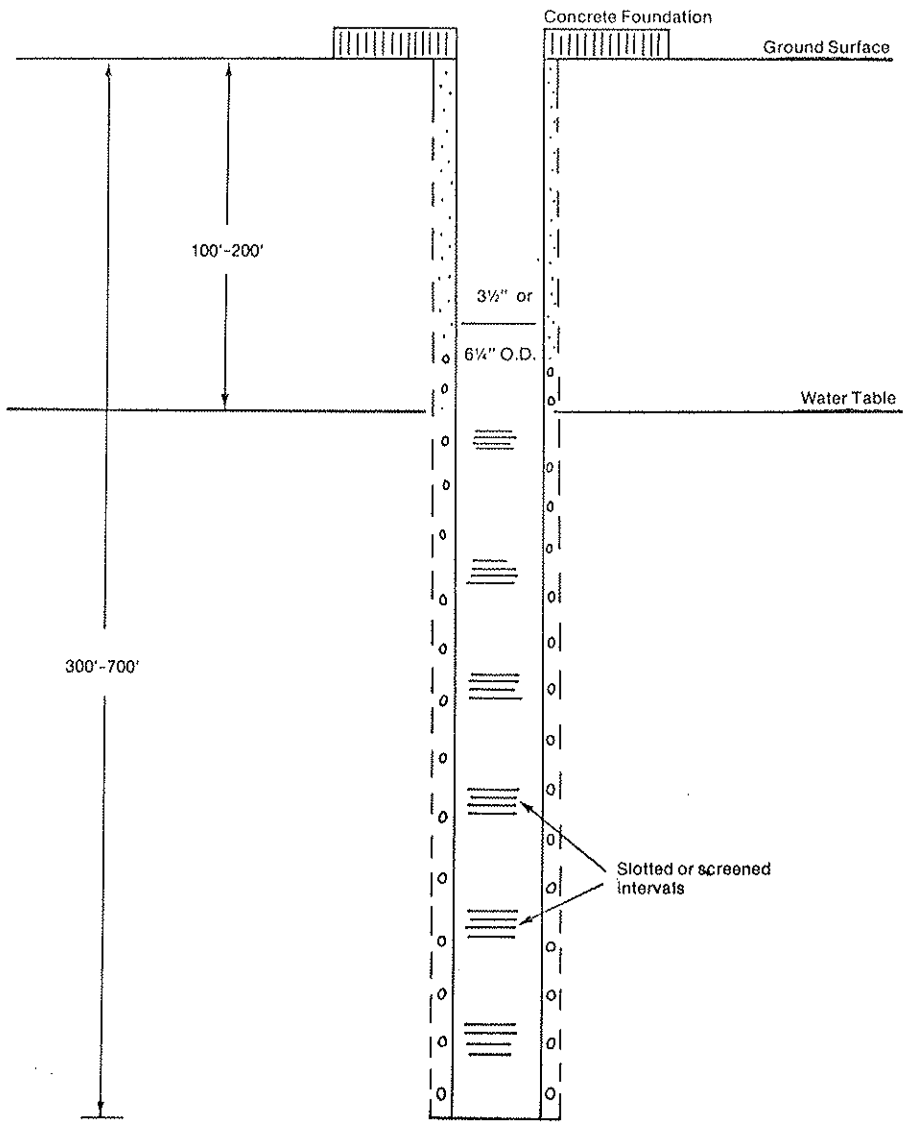

Fig. 2. 'Single' Observation Well

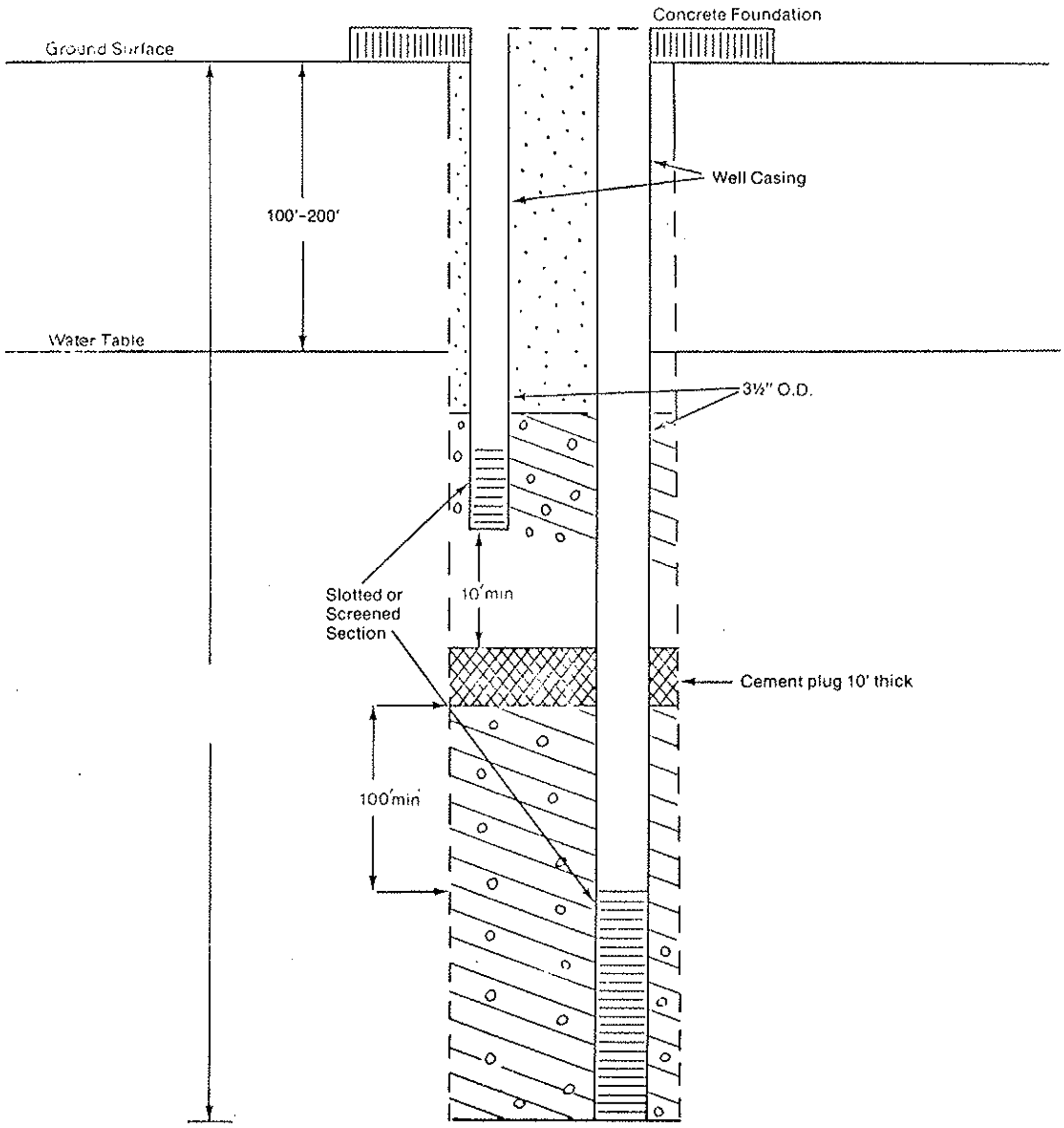

Fig. 3. 'Dual Observation Well'

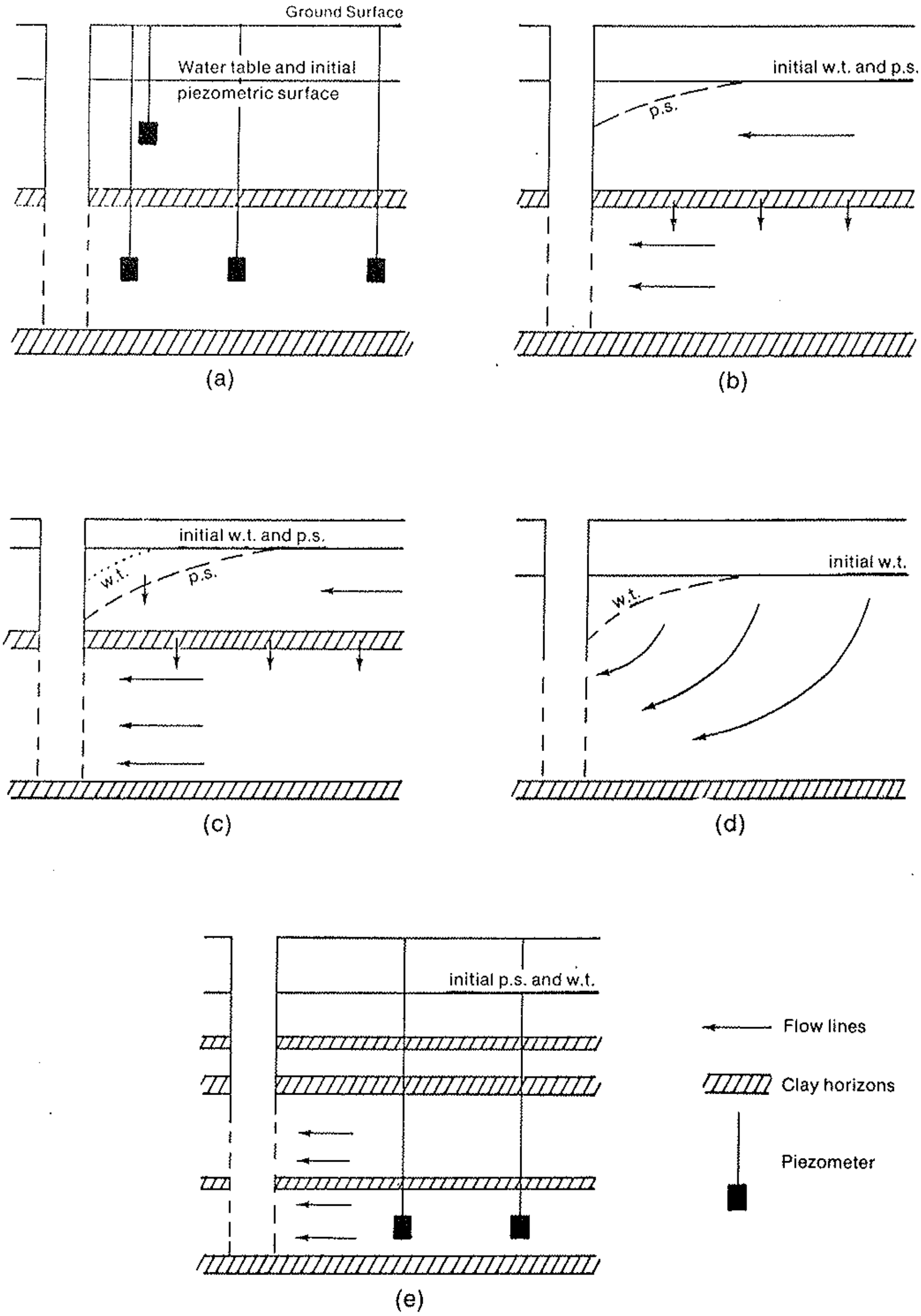

Fig. 4. a-e Schematic cross-sections to illustrate conditions in P. M. M. aquifer on abstraction

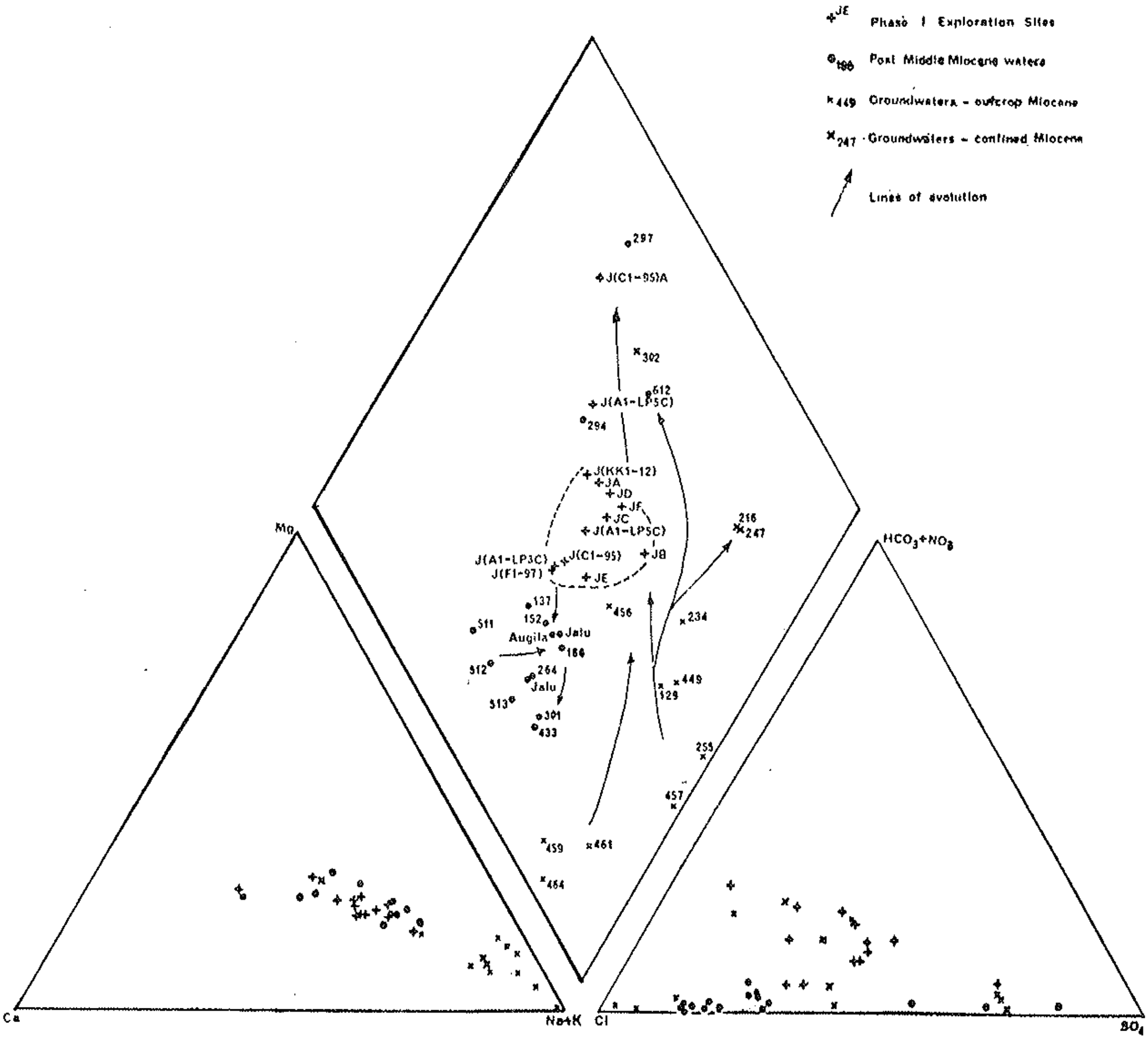

Fig. 5. Trilinear plot of representative ground water in the Phase 1 Area with possible lines of evolution. Numbers refer to Phase 1 drilling sites or to IGS reference numbers listed in Appendix 12.

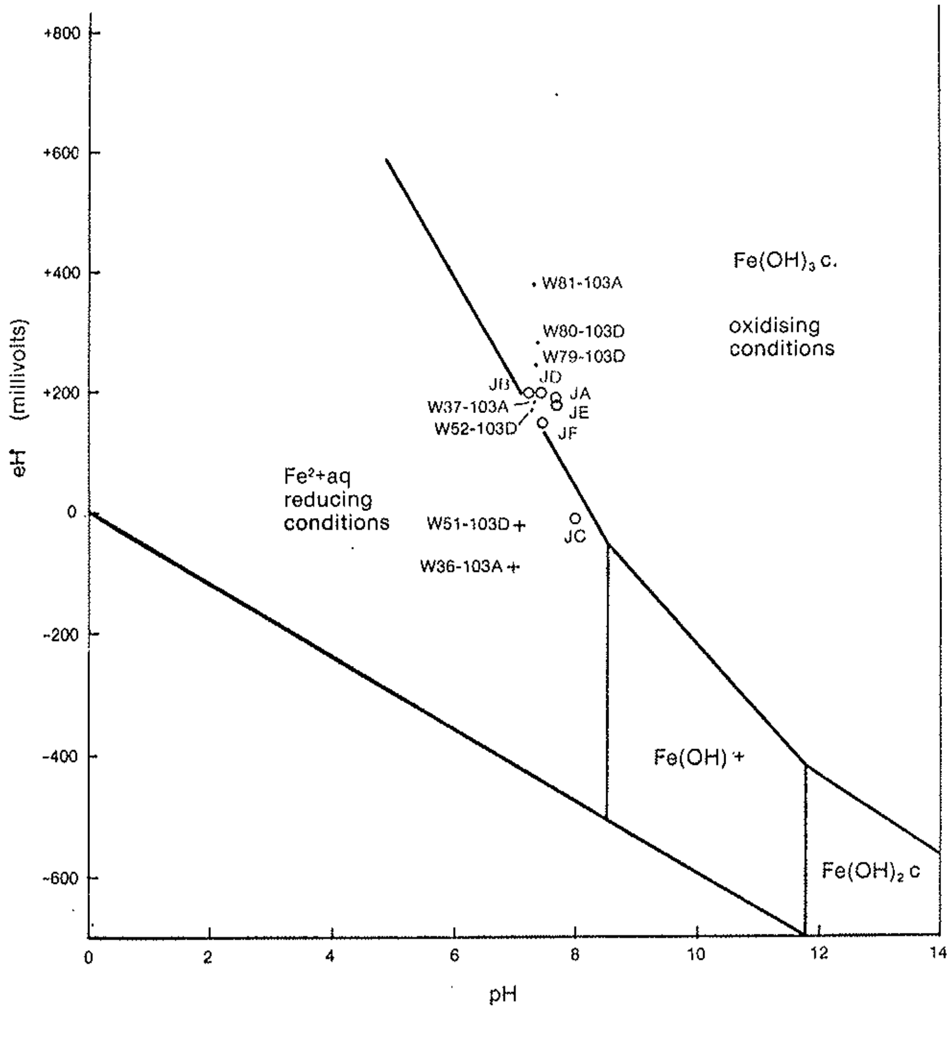

Fig. 6. Stability field diagram (eH - pH diagram) showing ferrous-ferric species and assuming 2×10^{-7} molar activity of iron. Phase 1 P. M. M. pumped wells (dot and circle) are distinguished from other shallow wells in Concession 103 (dot) and from deeper Miocene/ Oligocene wells also in Concession 103 (cross)