Libyan Arab Republic

Kufra and Sarir Authority

Jalu - Tazerbo Project: Phase 2

FINAL REPORT

by

E P Wright

with

4 APPENDIXES

Hydrogeological Department

Institute of Geological Sciences

Exhibition Road, London SW7 2DE

1975

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.

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PREFACE

This Report was commissioned in 1971 by the Kufra Agricultural Project, now known as the Kufra Sarir Authority. The study has been concerned with the hydrogeology of two regions known as Phase I (Jalu/Augila Region) - and Phase II (The Sarir/Tazerbo Region). An interim report on the Phase I region was presented to the Authority in 1973 and the final report on the Phase I Region as well as the report on the Phase II Region are now submitted to conclude the Institute's Commission.

The work has been undertaken under the general control of the Institute's Chief Hydrogeologist Mr D.A. Gray and under the direct supervision of Dr E.P. Wright. Investigations in Libya and in the United Kingdom have been undertaken by numerous staff of the Hydrogeological Department: Dr E.P. Wright, Dr R. Kitching, Mr A.C. Benfield, Dr W.M. Edmunds, Mr K.H. Murray, Mr M. Price, Mr I.B. Harrison, Mr J. Black, Mr I. Gale, Mr P.J. Chilton, Mr D.R. Giddings, Mr J. Shedlock, Mr T.R. Shearer, Mr P. Hillyard, Mr J. Worth, Mr P.K. Murti.

Drilling contracts were let by the Kufra Organisation and supervised on their behalf by the Institute's team. Drilling was undertaken entirely by the African Drilling Company of Tripoli. Due to various delays in drilling contracts the original study by the IGS was extended from a nominal period of twenty four months to thirty eight months.

The Institute acknowledges with thanks the assistance received throughout the Project from the Director General and staff of the Kufra and Sarir Authority. Also acknowledged is the considerable help provided by various oil companies listed in the Report and their staffs.

Kingsley Dunham
Director

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CONTENTS

TABLES

FIGURES

Jalu--Tazerbo Project: Phase 2

FINAL REPORT

E P Wright

1. INTRODUCTION

The IGS studies on behalf of the Libyan Government commenced on May 18th 1971 and concluded on July 31st 1974. The studies have been concentrated in two areas, designated Phase One (1) and Phase Two (2) (Figure 1). The Phase 1 Area studies are discussed in two earlier Reports (Wright, 1973; Wright et al, 1974).

The Phase 2 Area extends between latitudes 25° and 28° North and longitudes 21° and 22°45' East. Test drilling commenced in February 1973 and is still continuing. Supervision of the drilling contractor (African Drilling Company) during the Phase 2 operations was carried out by staff of Messrs Tipton and Kalmbach, Inc of Denver, Colorado, USA, until April 1974. IGS and Kufra and Sarir Authority staff supervised and participated in specialised aspects of the work such as lithological sampling and pumping test measurements. IGS field staff were gradually phased out and from February 1974 field observations were continued solely by the Kufra and Sarir Authority's geological staff. A list of IGS and KSA geological staff participating in the Phase 2 field investigations is given below.

a) Institute of Geological Sciences

Dr E P Wright	Principal Scientific Officer: Project Leader
Mr K H Murray	Senior Scientific Officer
Mr J Black	Scientific Officer
Mr I Gale	Scientific Officer
Mr J Shedlock	Scientific Officer
Dr C M Bowler	Scientific Officer (Temporary engagement)

b) Kufra and Sarir Authority

Mr S M Hasnain (Senior Geologist)

Mr S Ahmed

Mr M M Milad

Mr M Makhyoun

Test drilling in the Phase 2 Area has been limited to date to the area north of 26°30'N. A list of all sites drilled by July 31st 1974 is given below and details of the four sites completed are contained in Appendices 1-4 with this report.

a) Exploration Boreholes

(i) T (Q1-65) A. (Appendix 4)

b) Exploration/Production Test Sites

(i) T (U1-65) : two observation wells and one production well (Appendix 1)

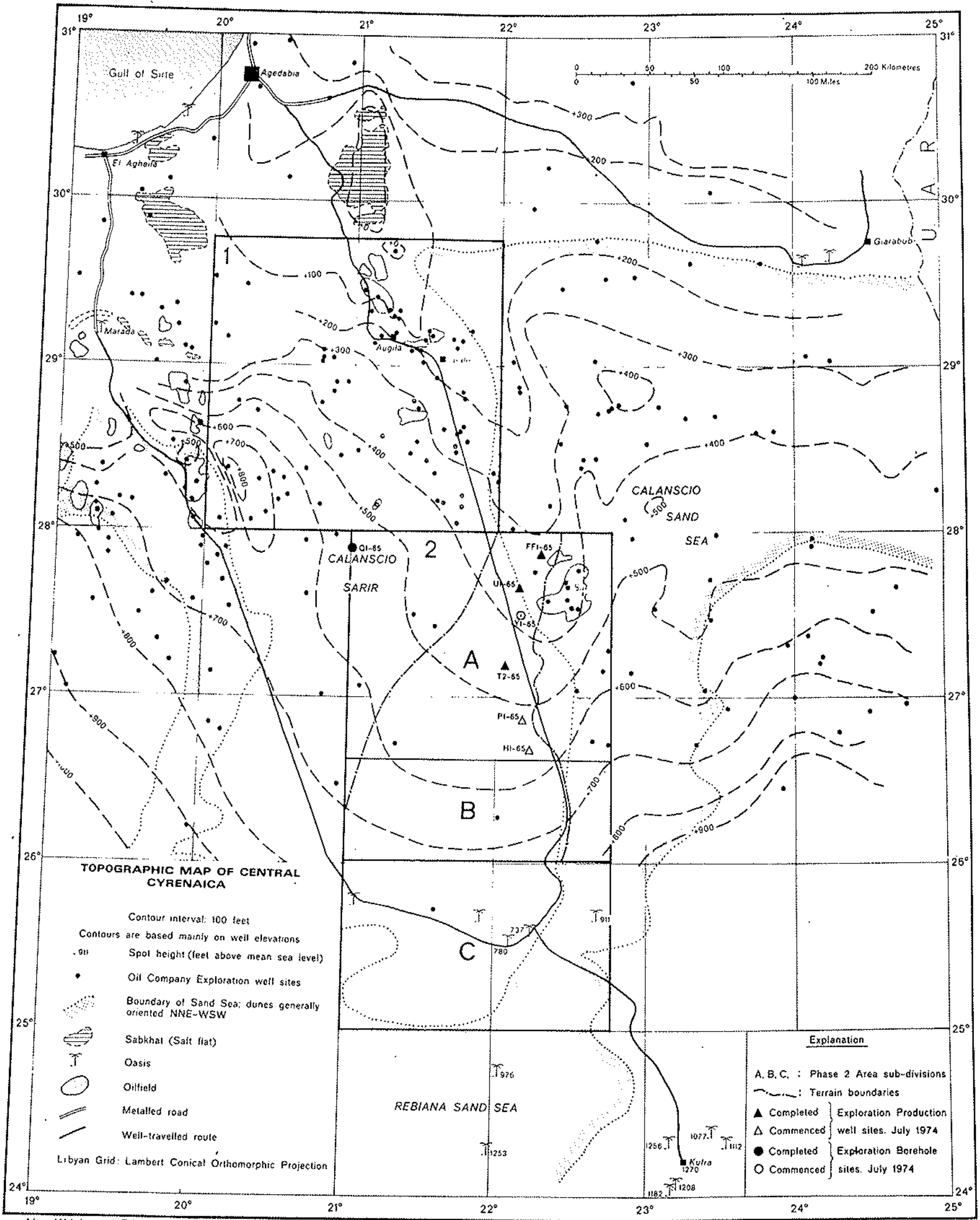
(ii) T (FF1-65) : two observation wells and one production well (Appendix 2)

(iii) T (T2-65) : two observation wells and one production well (Appendix 3)

(iv) T (P1-65) : one observation well; production well planned

(v) T (H1-65) : one observation well; no production well planned

An irrigation project for 50, 000 hectares is proposed in the northern Phase 2 Area requiring 500 production wells. A contract to drill 300 of these wells has been let and drilling commenced during May 1974. A provisional well field has been designed by Tipton and Kalmbach on the basis of information available in early 1974, and it is planned that 50 production wells will be



After Wright and Edmunds, 1969.
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FIGURE 1

Figure 1. Topographic Map of Central Cyrenaica

completed before the end of the year. The well field is located in the Calanscio Sarir west of the Calanscio Sand Sea and the wells are sited in two main lines trending north-south, 120-140 km long and 20-30 km apart. In view of the delay in the preliminary exploration drilling and the uncertainty of the aquifer's characteristics and response, it has been decided to drill the first six production wells at scattered locations, each with two associated piezometers of a design suitable for aquifer testing. To date (August 1st 1974) all piezometers at 6 sites have been drilled but as yet no production wells. The remaining forty-four production wells of the first group of 50 are to be located in the main central well field area where conditions appear to be most favourable. It is recommended that the spacing between these wells should be several times the final anticipated spacing. Additional wells can subsequently be located in between if site conditions prove favourable.

This Report was prepared between May and August 1974. Mr K H Murray assisted in the preparation of the Appendices and Mr Gale and Mr Murti assisted in the analysis of geophysical logs and the preparation of associated maps and sections. For reasons of time, many of the maps have been prepared by computer techniques.

2. METHODS OF INVESTIGATION

Descriptions of the basic methods of investigation for the Phase 1 studies were included in the Interim Report (Wright, 1973). The procedures during the Phase 2 activities were broadly comparable with some modifications and additions determined by the different conditions prevailing.

2.1 Field Survey

The Phase 2 Area extends mainly over the original B. P. Concession 65. All water wells in this area existing up to May 1968 had been visited and basic measurements taken in previous IGS investigations during 1967-68. A few additional wells have been drilled since that time and these were visited during the current investigations. A programme of selective gamma ray logging has also been carried out.

2.2 Geological Records

Data was abstracted from the oil company records and logs for relevant oil exploration and water wells. The well logs include a Lithologic (mud) Log based on drill cuttings, several types of geophysical log and a Final Lithologic Log which also incorporates any available stratigraphical data. The geophysical logs mainly utilised have included IES (spontaneous potential, 16 inch normal and induction), gamma-ray, neutron and sonic.

In the Phase 2 Area, potential aquifers exist in the Post-Eocene sequence and in the older Nubian Sandstone but the more detailed studies have been limited to the former. The Post-Eocene is of limited interest from the viewpoint of oil exploration and in consequence recorded and analysed lithological characteristics in well logs are brief and generalised. For the purpose of this study a detailed appraisal of the relevant sections of available logs was carried out and the following lithological subdivisions within the Post-Eocene sequence recognised and recorded:- sands (s), clayey sands (cs), sandstones or low porosity sands (ss), sandy clays (sm), clays (c), sandy carbonates (sc) and carbonate rocks (d - dolomite; l - limestone). The symbols in brackets are those utilised in cross-sections and litholigical logs. Sands have a low gamma response and high total porosity (deduced from sonic, neutron or electric logs). Clayey sands have a higher gamma response but are otherwise similar. Results to date have not indicated any significent reduction in permeability in clayey sands as compared with sands of comparable grain size and distribution, and some other cause may exist for the relatively high gamma response other than dispersed clay content. It is possible that the clay occurs in thin streaks which may not significently affect the horizontal permeability although the feature would be expected to decrease the vertical permeability. Sandstone or low porosity sands are mainly recognised from the neutron log and less markedly so from electrical or sonic logs. Confirmation of the presence of sandstone is sometines provided by the Company lithologic logs or from samples collected during the test drilling. In other cases the presence of cement cannot be inferred and the sonic log only rarely indicates a significent degree of consolidation. The cement is carbonate and presumably all gradations exist between calcareous sandstones and sandy carbonates. The occurance of cement is very significant from the hydrogeological viewpoint but the relations are not clearly understood and it seems likely that calcareous sandstones are more abundant than can be readily inferred from the logs. In general it would seem that fine sands are more permeable than calcareous sandstones of equivalent porosity. Most significantly also, the permeability of fine sands can be estimated from size analysis whereas cemented sandstone cannot. Judging by the logs, cementation tends to be rather variable with sandstones occurring in thin bands alternating with unconsolidated sands. Sandstones occur more commonly in the Lower and Middle Miocene than elsewhere in the Post-Eocene sequence. On the assumption of carbonate cement and quartz sand, the proportions of the two minerals should be capable of resolution by a crossplot of neutron porosity and one other porosity log. Unfortunately calibration of the type of neutron logs available - (GNT with Ra-Be source) preferably requires core data for good resolution. The other porosity logs which include electrical and sonic have also proved of very coarse definition in these unconsolidated or weakly consolidated formations. Clays are indicated by high gamma response and sandy clays by intermediate or fluctuating gamma. In the mud logs, clays are commonly referred to as sandy or silty. The occurrence of shale as opposed to clay is rarely noted. High gamma response is sometimes anomalously associated with low neutron porosity and may indicate an argillaceous limestone. Sandy carbonates grading to carbonates are readily apparent in drill cuttings and on the logs are generally distinguished by low neutron or sonic porosity and high resistivity. Unless recorded as such on Company Lithologic Logs, sandy carbonates cannot be readily distinguished from sandstones by the geophysical logs alone although as noted above it should be possible to do so by appropriate cross-plots.

Semi-quantitative indications of porosity are utilised in distinguishing sandstone or fine sand based mainly on the neutron log response and to a lesser extent on the sonic and resistivity logs. Calculations of porosity have been made using available standard Schlumberger charts. The calculated porosities are in most cases excessively high, and the relat e variations except for extreme cases are not great. More refined c l-culation than those described below may be worth attempting but would certainly require the production of calibration curves either based on measurements on core samples or by correlation with data from more sophisticated logs such as SNP, Formation Density, micrologs etc from which more accurate porosity values can be obtained.

2.3 Porosity Determinations From Geophysical Logs

(a) Neutron: The neutron logs generally available are from GNT tools with a Ra-Be source. Calibration is not easy and the appropriate departure curves are not currently available since the tool is outdated. The neutron response does appear to be the most sensitive in these unconsolidated formations and it is hoped to make improved porosity calculation when the departure curves requested from Schlumberger become available.

(b) Electrical

1 By Porosity Index from the 16 inch normal and resistivity departure curves (Schlumberger, 1962). The method is based on the assumption that the R16" is equivalent to Ri (the resistivity of the invaded zone) when corrected for the influence of the borehole. The ratio Ri/Rm (Rm = mud resistivity) is correlated with a Porosity Index and adjusted by a multiplier 'C', to obtain porosity. The multiplier 'C' is determined by chart from the SP reading.

2 By Formation Factor determined in this instance as Ro/Rw where Ro equals the resistivity of the saturated formation (from the induction log) and Rw the resistivity of the formation water (from electrical conductance measurements). Porosity ( ) is then determined by the Humble Formula where

$$F = \frac{0.62}{2.15}$$

(c) Sonic: Porosity can be determined from the interval transit time and since Δt for shale is greater than 100 μ sec/foot, a correction for lack of compaction is required. In most cases, the apparent values of Δt are outside the range of the Schlumberger calibration curves in the standard chart book.

As noted above, the results of the analyses all show very high values of porosity in the general range 30-50%. Improved values would require better calibration curves. The porosity index methoa is not considered very accurate in this instance as there are indications that R16" is not providing a good value of Ri. This could be checked by examination of appropriate departure curves for varying values of Ri/Rm and Rt/Rm (not available at IGS). Porosity from Formation Factor determinations should provide moderately accurate data in the clean sand sections but the Formation Factor would be better determined by micrologs. The induction value is not thought likely to provide a good value for Ro.

2.4 Test Drilling

2.4.1 Location and Type

Test drilling in the Phase 2 Area was scheduled to commence in October 1972 but due to various delays did not commence until February 1973. A considerable sense of urgency has been maintained throughout the subsequent period since it was decided in early 1973 to award a contract to drill 500 production wells in the Phase 2 Area to provide water for local irrigation.

From soil considerations based on reconnaissance surveys carried out by Mr A L Craig, Chief Engineer of the Kufra and Sarir Authority, the Phase 2 Area was subdivided into three zones, 'A-C' (Figure 1), of which 'A' was to be given priority since it was there that the first well field would be located. Zone 'A' is bounded to the east by the dune sands of the Calcanscio Sand Sea and to the west by a general line beyond which surface calcrete occurs to a significant extent. Zone 'A' was scheduled for initial test drilling with subsequent drilling to be done in zones 'B' or 'C' if time permitted.

Three types of drilling site were proposed, varying in accordance with depth or mode of completion of the test wells. All sites were planned to be located at existing oil exploration well sites in order to make use of existing geophysical logs. The three types are as follows:

1 Exploration/Production (E/P) well sites which include a high capacity production well and one or more observations wells. The first observation well is drilled to maximum depth of the productive section of the aquifer, not exceeding 1000 feet, and lithological samples collected from the water table to total depth. The production well is screened over an interval considered capable of providing a discharge in range 750-1250+ gallons per minute but consideration is also given to selecting an interval which will enable boundary conditions to be recognised for the purposes of an aquifer test. The first and second observation wells are completed in accordance with the site conditions. E/P sites are designed for location in Zone 'A', the main area of agricultural potential. Five E/P sites have been drilled of which three are completed. In the case of the fifth, T (HI-65), the results of drilling the first observation well were such that further drilling was not recommended.

2 Exploration (E) Sites include a single exploration well drilled to less than 1000 feet and sampled in the manner described for the first observation well at an E/P Site. The well is cased and may be a single or dual piezometer type. Final completion including selection of levels for screens and in-hole cement plugs will depend upon the proposed use of the well. This could be multi-purpose to include water quality information at varying levels, for use during a short-term pumping test in association with nearby Company water wells and as a long-term observation well. For the first purpose, screens set at selected intervals within the aquifer system are required; for the second, screens are set opposite the same responding interval as in the Company water wells and additionally provision must be made to isolate such screens within the hole and also within the casing (packer combined with pressure transducer and direct measuring systems); for the third purpose screens set and isolated at the water table are required. Exploration sites are intended to be located outside the main area of agricultural potential and designed to obtain good information on the aquifer's characteristics without the expense or time requirements of a high capacity production and two observation wells.

3 Exploration Boreholes (EB) Sites are deep exploration holes to be drilled to the base of the Post-Eocene succession or through the Nubian in the southern Phase 2. The main purpose is to collect good lithological samples and to obtain reliable information on water quality. Exploration Boreholes are designed with long-term considerations in mind which may include water supplies for piping or for in-situ use. The one hole completed at T (Q1-05) at the north-west corner of the Phase 2 Area was sited in connection with possible development of both deep and shallow aquifers within the Post-Eocene system for large-scale water supply to the coast. Sites selected in Zone 'A' are designed to obtain information on the deep aquifer which may eventually be required to boost supplies for local irrigation or for piping elsewhere. Sites in Zone 'C' are to obtain information on the Nubian.

No exploration (E) sites have been drilled. Probable future locations will be to the west and east of the main well field and designed to obtain general lithological information and to serve as long term observation wells to monitor static levels at the water table and, particularly in eastern areas, to monitor water quality changes at depth.

2.4.2 Design of Test Wells

2.4.2.1 Exploration Boreholes

The final completion depends largely on the methods utilised to obtain the desired information. At T (Q1-65)A, the hole was completed with $6\frac{1}{2}$ inch casing screened at 6 selected intervals with 30 feet lengths of torch-slotted and mesh-wrapped casing. These screened intervals were developed by swabbing and produced by air lift using a straddle packer to isolate a particular interval. It was assumed that communication would be largely with the aquifer section opposite the particular screened interval. Cement plugs could have been set outside the casing to ensure this situation but it would have been difficult and time consuming and was considered unnecessary. The method of completion provided samples of water from various depths, a value of hydraulic head at each depth, and some indication of permeability on the basis of production rates and drawdown. The method described proved effective but costly and it is hoped in the future to make use of in-hole packers emplaced during drilling. A hole could eventually be abandoned after selective intervals are sampled for water analysis, or possibly completed by screening at the water table for long-term observations.

2.4.2.2 Exploration/Production Wells

These have been of the same basic design as in the Phase 1 Area with 16 inch well casing and 8 inch diameter screen. For ease of emplacement, Hagusta screen with a pre-pack filter has been used. The relative lengths of screen and casing are chosen in accordance with the hydrogeological conditions at each site with a view to obtaining information on the productive capacity of wells completed in this manner and at the same time conforming to the geological boundary conditions to permit a reliable aquifer test using any existing Company water wells. A critical aspect in the completion design is the size of the well casing permitting the use of down-hole flow velocity devices and the measurement of pumping water levels.

2.4.2.3 Observation Wells

These are mainly of dual piezometer type. They differ from the basic design described in the Interim Report (Wright, 1973), by including more in-hole cement plugs emplaced to prevent communication between different levels. For ease of emplacement, Hagusta 80 mm screens have been used in the long strings and Johnson 5 inch slotted screen in the short strings. The use of Johnson screen was required on account of the difficulties of emplacement of two pre-pack screens in opposing strings.

2.4.3 Drilling Procedures and Lithological Sampling

Drilling was carried out by rotary rig. The exploration boreholes, all observation wells and the upper cased sections of production wells have been drilled using Quiktrol mud, a type designed to produce a very thin wall cake and negligible invasion. The mud is eventually degradable and supposedly easy to disperse. The screened sections of the E/P wells were required to be drilled with Revert mud which was used successfully in the Phase 1 drilling. Because of high temperatures, the Contractor requested permission to mix Quiktrol with Revert in the drilling of T (U1-65)P. As far as is known, Revert only was used in drilling the screened sections of the other E/P wells completed to date. Quiktrol was used throughout in the deep production well at T2-65 completed experimentally with a fibre glass slotted screen. Specific capacity was greatly improved in this well by the use of a mud dispersant in accordance with the suggestion of the Tipton and Kalmbach drilling engineer. The efficiencies of the E/P wells in the Phase 2 Area appear appreciably lower than those in the Phase 1. The use of a mud dispersant could presumably have improved the one well drilled with a mud combination of Quiktrol and Revert. For Revert alone the appropriate breakdown agent (Fastbreak) should have been sufficient.

Lithological samples were collected in accordance with the established method described in the Interim Report (Wright, 1973). Coring has been attempted at several sites but successfully only within more consolidated Miocene formations at T (Q1-65).

2.4.4 Grain Size Analysis

Samples have been prepared and sieve-analysed as described previously (Wright, 1973). Tabulated data presented in this report include the D50 and D90 sizes in microns and the uniformity coefficient (D40/D90). More detailed analyses have included the preparation of size frequency curves, cross-plots of median diameter and standard deviation to calculate permeability (Kgs) according to the method of Masch and Denny, 1966, and cross-plots of standard deviation against mean diameter and skewness to determine depositional environment (Moiola and Weiser, 1968).

Samples containing significant proportions of cemented material are not analysed. Where cemented material constitutes a small proportion which is usually apparent in the top sieve, it is preferable to note the amount but to discard for the purpose of sample analysis. It is assumed that the consolidated material is unrepresentative of the main formation although the occurrence is significant and must be recorded.

The one core sample of weakly consolidated sand was subjected to laboratory tests designed to determine permeability and porosity. The tests proved unsuccessful due to insufficient strength of the sample.

2.4.5 Aquifer Testing

Some modifications to the design and procedures of pump testing for aquifer analysis were included in the Phase 2 operations as compared with the Phase 1, on account of the greater heterogeneity of the aquifer to be tested. In the Phase 1, testing was limited to the relatively homogeneous unconsolidated sand formations of the Post-Middle Miocene, whereas in the Phase 2, formations within the Lower and Middle Miocene required to be included. The full sequence at a site may include a variable assortment of unconsolidated sands, clayey sands and calcareous sandstones grading to sandy carbonates. Clays and sandy clays will form boundary aquicludes or semi

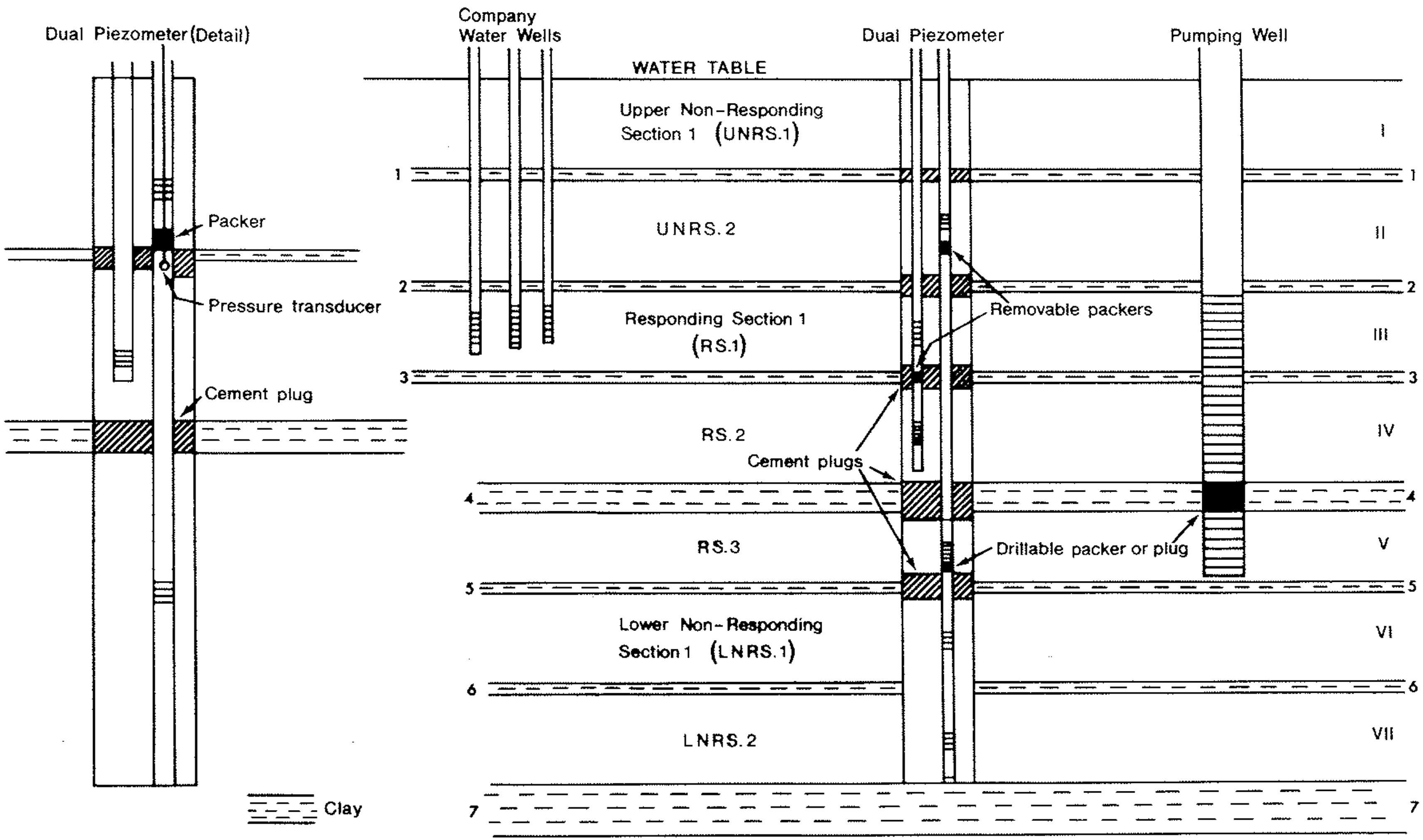

Figure 2. Schematic section to illustrate pumping test site design in multiple aquifer system

permeable layers separating more permeable formations. Testing of a thick multi-component sequence with a limited number of observations wells presents certain difficulties. The methods adopted can be most easily appreciated by consideration of the schematic sequence shown in Figure 2. The aquifer sections numbered I-VII may include any of the permeable formations listed above and are separated by clay horizons. The subsidiary aquifers will have variable transmissibilities and storage coefficients and the localised response of an individual interval during abstraction will depend on such factors as the presence or otherwise of a screen, the head differentials developed across the boundary clay layers and the latters' permeabilities. The clay layers in the PMM sequence are generally in the range 5-15 feet thick and in the section which requires to be cased out to provide adequate drawdown (100-200 feet), some 2-3 clay layers are to be expected.

To obtain defined boundary conditions, casing and screen are set in accordance with significant clay layers, and in the schematic example, Figure 2, the well casing is set and cemented down to clayer layer 2. The length of screen below this level will depend on several factors, some conflicting. The results of drilling the first observation well may have shown that intervals V1-VII are unlikely to be very productive. Layers III-V are therefore considered most favourable, but for the purpose of aquifer testing with a limited availability of observation wells, a restricted screening might appear more advisable. Company wells for example are shown screened in interval III only. A compromise solution can be attempted by drilling the production well to a deeper level (above clay layer 5) in accordance with the general indications of the lithological samples. Two aquifer tests can then be carried out, one utilising the full length of the screen, the second after backfilling or setting a temporary plug in the screen at clay layer 4. Alternatively, only one test need be carried out with complete reliance being placed on the abstraction rates from the appropriate intervals being determined by flow velocity logging. The latter method may have certain advantages in that interaction across clay layers may be reduced in consequence of comparable head drops within the intervals.

Drawdown analysis of particular observation wells must be carried out in relation to the particular responding intervals in which they occur and on the assumption that an interval can be treated separately. Problems in this approach include the necessity to obtain good flow velocity data and the uncertainty of a response interval due to possible discontinuity of a clay layer. Checks on the assumptions can be made by head observations in the 'non-responding' intervals above or below the main responding intervals. A possible alternative approach would be to screen an observation well at several levels in a heterogeneous sequence and to assume that the integrated drawdowns will give an average transmissibility for the entire sequence. The method has doubtful validity and in any case is less informative.

The former method was adhered to and typical procedures can be appreciated by reference to Figure 2. Screens set in intervals VI and VII are mainly required for water quality information and prior to aquifer testing, the casing would be plugged above. The long string in the dual piezometer is monitored at two levels, within 3 by pressure transducer and within 2 directly. The short string has screens straddling two intervals with a thin clay layer in between. Both levels could be monitored if convenient by a pressure transducer-packer system but if grain size characteristics of intervals III and IV are comparable and abstraction rates similar, then this would be unnecessary although the measurements would be confirmatory. By the same token, the screens set in the Company wells in 1 could relate equally well to 1 or to both 1 and 2 assuming comparable head changes.

Results of actual tests will be discussed in the section on hydraulic parameters but some results are relevant to the present discussion. Unlike the leaky response of the Phase 1 wells, all drawdown data for the Phase 2 tests have shown a fully artesian response for the five days duration of pumping. Whether this indicates less permeable confining layers is not yet certain. Very minor drawdowns have usually occurred in the immediately adjacent 'non-responding' intervals implying some outflow but it is considered significant that the drawdowns in the NR layers have also an artesian form. That being so, the low drawdowns are regarded as probably indicating relatively minor flow across the intervening clay layer since they will relate to an artesian storage coefficient. Transmissibility of course also needs to be taken into account. The artesian drawdowns in the responding intervals give added confirmation.

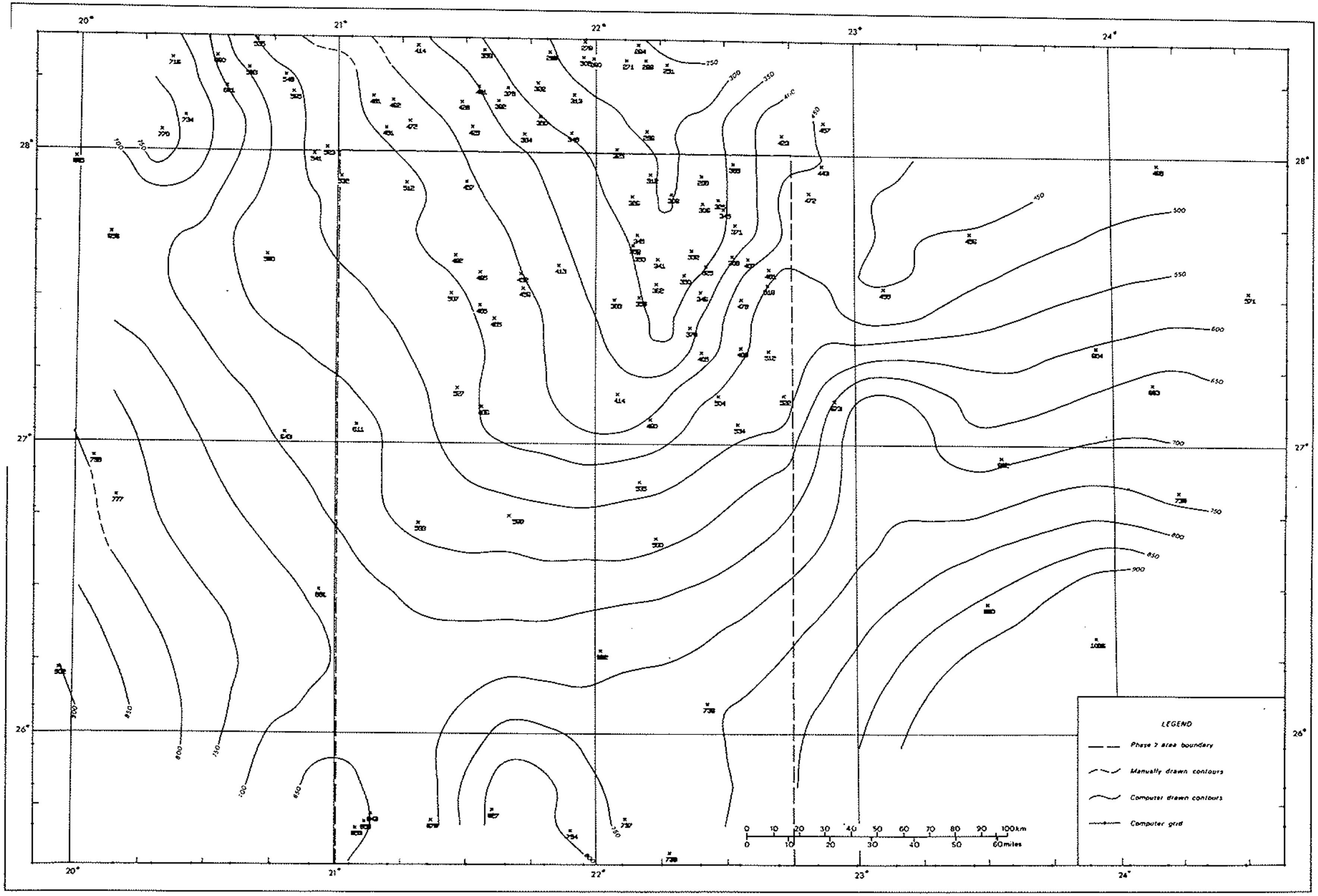

Figure 3. Topography Phase 2 Area (computer plot)

3. PHYSIOGRAPHY

The contours shown in the regional topographic map of Central Cyrenaica (Figure 1) are based on ground elevations at scattered oil exploration sites. They take no account of the relative elevations of the sand dunes which commonly rise to some fifty feet or so above inter-dune levels. The star dunes at the southern end of the Calanscio Sand Sea are exceptional and may attain relative elevations of several hundred feet.

The most significant aspect of the general ground contouring is the broad trough-like feature which extends north-south and also corresponds with the maximum axial thickness of the Post-Eocene formations in the Sirte Basin. Dominant physiographic features of the Phase 2 Area are the Calanscio Sand Sea and Sarir and the hilly Palaeozoic outcrops in the south-east. Surface dissection of the former areas is not apparent from casual observation although the USGS topographical map shows a prominent wadi entering from the west on about latitude 27°00' North. The boundary of the Sand Sea in Figure 1 is based on information from this same map but the eastern margin of zone 'A' shows a more accurately defined boundary representing the edge of the dune sands. A transitional passage with sand cover but gentle undulating relief normally intervenes between the dunes and the gravel covered Sarir.

A larger scale map of the topography of south-central Cyrenaica including Phase 2 and marginal areas is shown in Figure 3. Its main use is in association with water table maps in order to determine depths to that surface. This is a computer printout map and the contours are controlled strictly by the available points.

4. GEOLOGY

The surface geology of Central Cyrenaica is shown in Figure 4. The Phase 2 Area is mainly covered by recent surface sands and gravels except in the south-east where outcrops of Palaeozoic and Mesozoic rocks occur. The main aquifers occur within the Post-Eocene Formations of the Sirte Basin succession and in the Nubian Sandstone Series. The latter extends beneath the Sirte Basin but occurs most significantly in the Kufra Basin which stretches from Libya into Chad, the Sudan and the United Arab Republic.

4.1 Regional Setting

The Kufra and Sirte Basins are sediment - filled troughs, the former including Palaeozoic and Mesozoic formations, the latter late Mesozoic and Tertiary. The sedimentary successions were deposited on the African foreland between the stable African cratonic shield and the mobile Tethys belt (Klitzsch, 1971).

The Palaeozoic and Mesozoic formations of the Kufra Basin are mainly sandstones and shales, continental or marginally marine in origin which developed in relation to a series of alternating troughs and uplifts controlled by essentially epeirogenic movements accompanied by some block faulting. The controlling structural trends are shown in Figure 5 and include NW-SE Caledonian trends of early Palaeozoic times and NE-SW Hercynian trends of late Palaeozoic and early Mesozoic. The main incursions occurred in the Silurian and Upper Devonian. Following Hercynian movements, the early Palaeozoic formations were eroded on uplifted areas and deposited in adjacent low-lying areas, notably in this instance the Kufra Basin occurring between the Tibesti-Sirte and Ennedi-Uweinat uplifts. In the Kufra Basin, Carboniferous formations are mainly continental since access to the sea had become increasingly difficult. Sediments of Triassic and Jurassic age are thought to be absent and the overlying Nubian is continental and probably in the main of Lower Cretaceous age.

The Sirte Basin occurs in north-central Cyrenaica. The basin was initiated in Late Cretaceous times and continued to develop with decreasing intensity throughout the Tertiary. The basin formed on top of the eroded Tibesti-Sirte uplift which collapsed to form a series of tilted horsts and grabens. The main fracture systems trend northwest-southeast to east-west (Figures 5 and 6). Sedimentation was initially complicated in relation to the variable topography of the basement floor and the associated faulting but subsequently became more uniform. The environment was initially mainly marine with increasing lagoonal and continental facies developing in Middle to Late Tertiary times.

The Sirte Basin may be divided into a northern mobile province and a southern stable province (Hea, 1971). The mobile province is that part of the basin mainly affected by rift faults which decrease in throw southwards and splay out against the stable province. The sedimentary successions progressively reduce in thickness southwards over the stable province and become increasingly continental in origin. A generalised geological cross-section is shown in Figure 7 (a) extending from Sarir Field in the central Sirte Basin to Uweinat in the Kufra Basin.

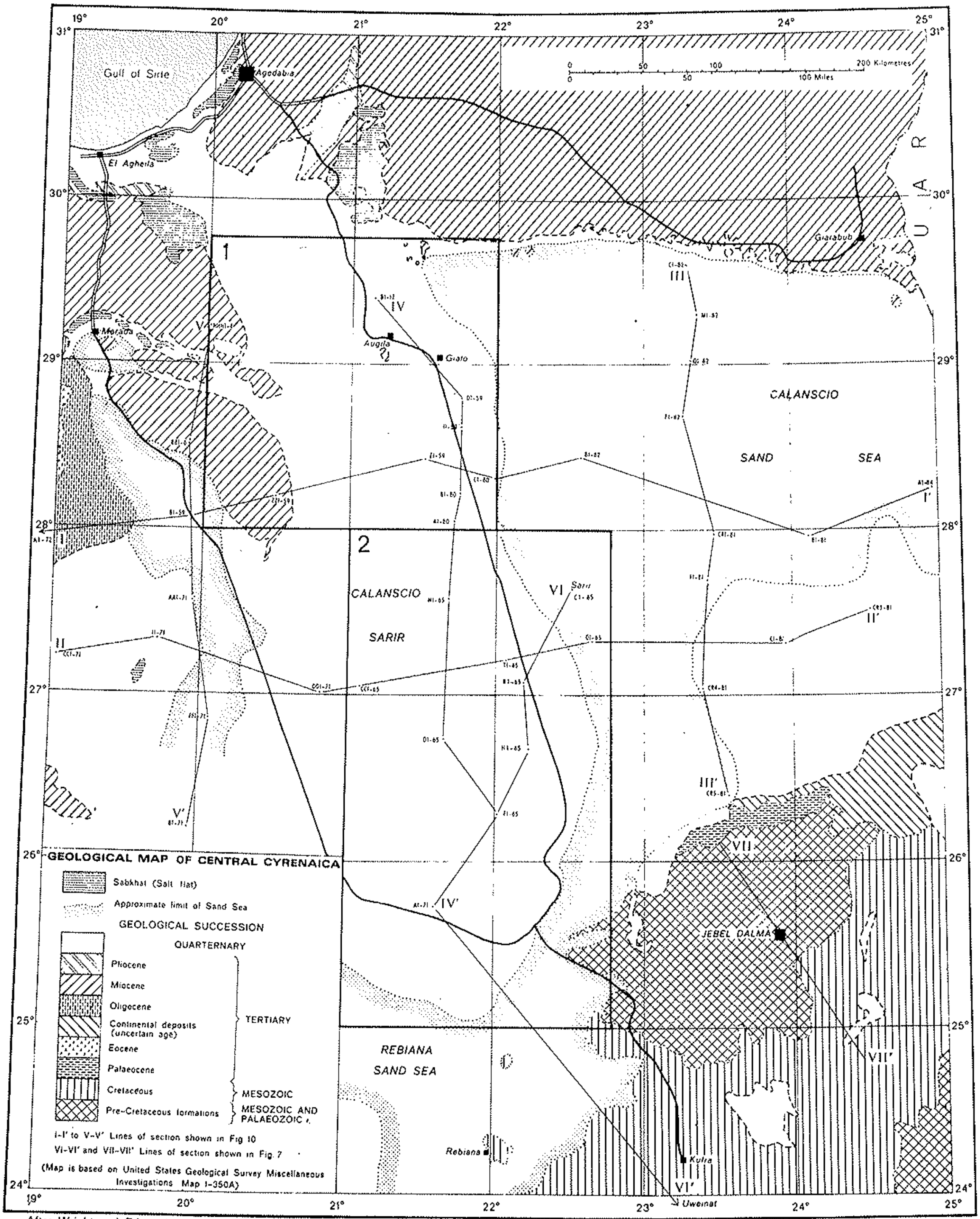

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Figure 4. Geological Map of Central Cyrenaica

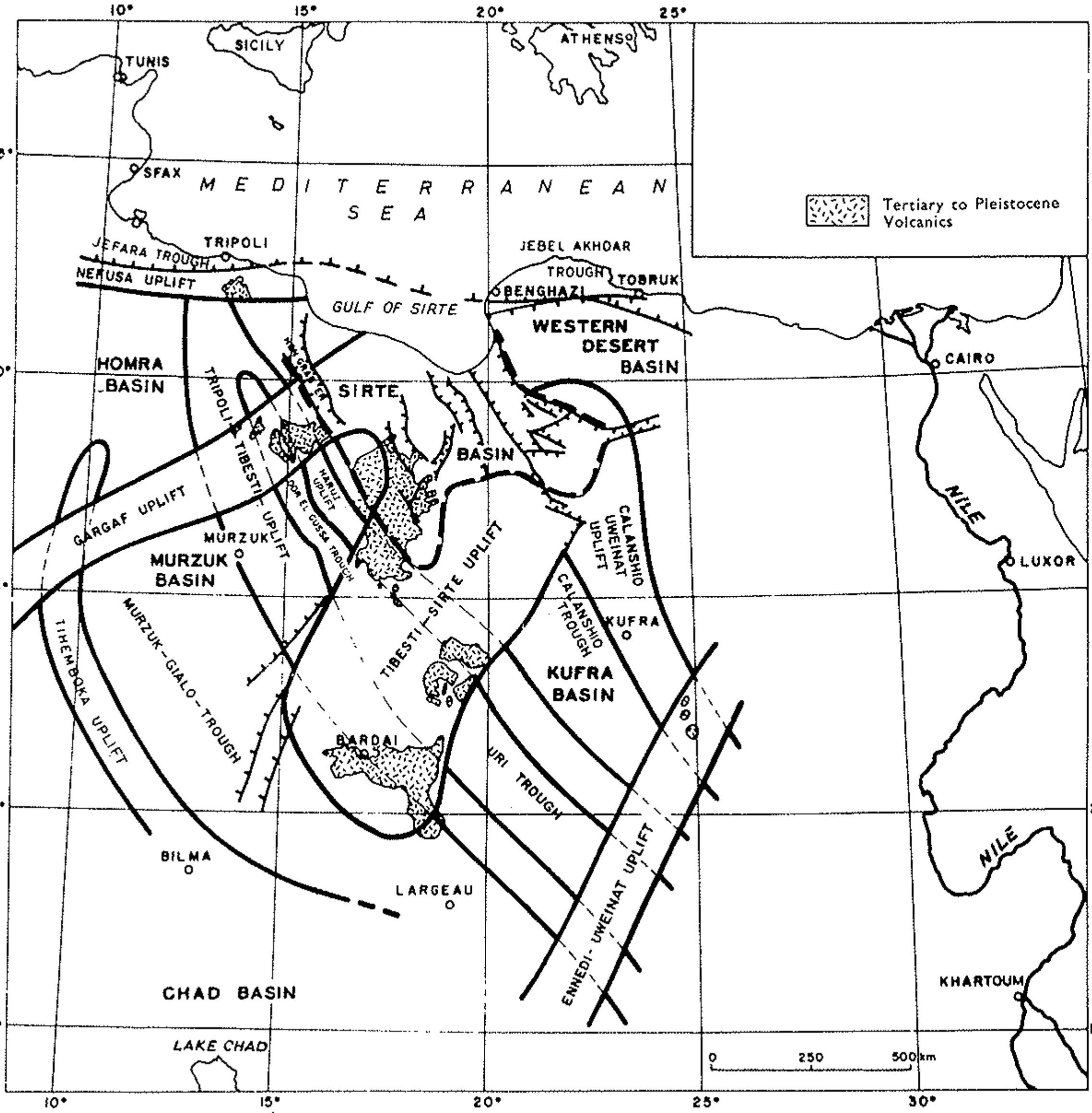


Figure 5. Schematic map of the major structural elements in Libya (reproduced from Klitzch, 1971). Caledonian trends are northwest-southeast; Hercynian trends northeast-southwest.

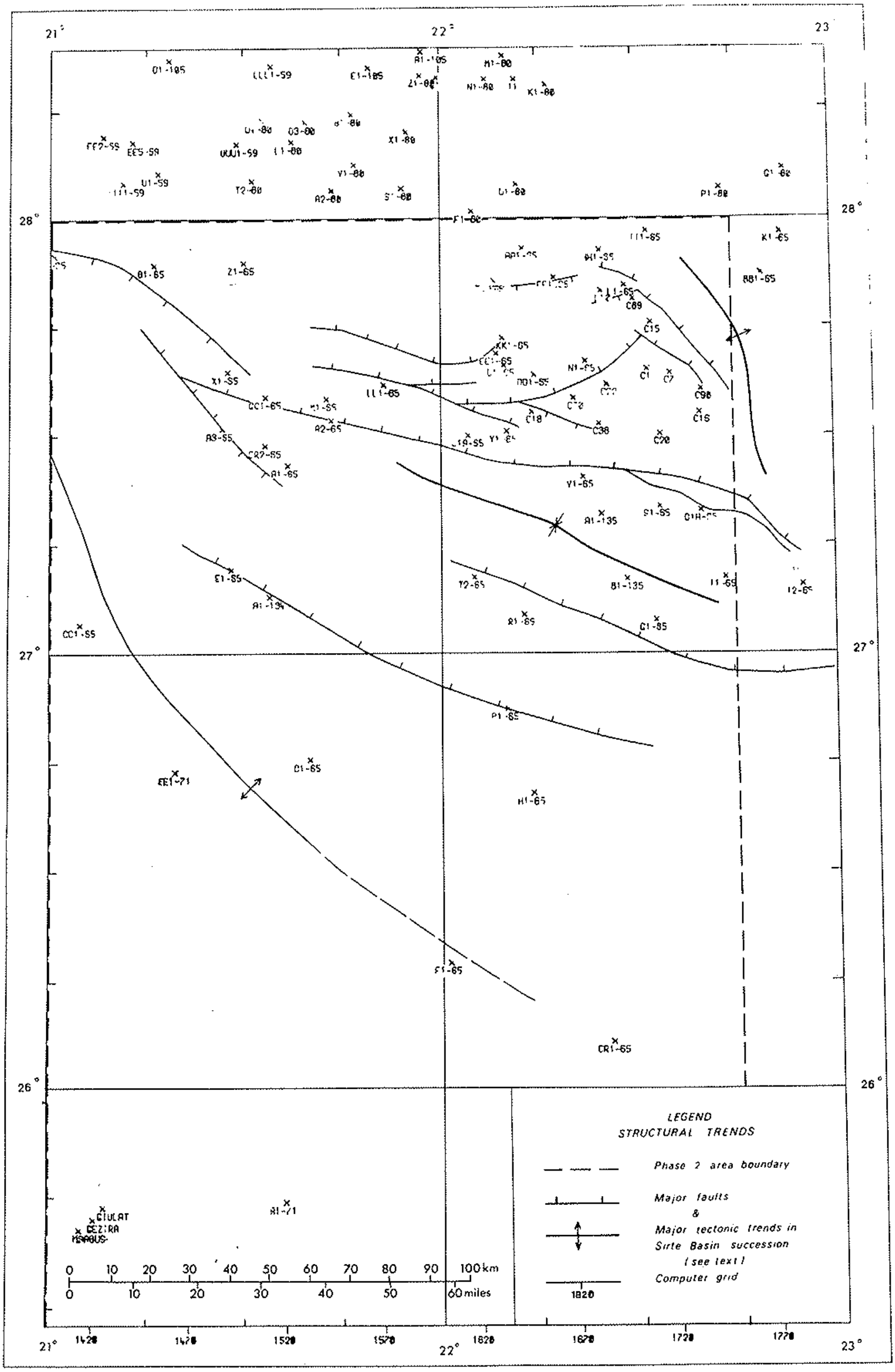


Figure 6. Structural trends in Phase 2 Area

4.2 Kufra Basin: Structure and Stratigraphy

The Kufra Basin is filled with continental to marginal marine Palaeozoic and continental Mesozoic sediments (Table 1) and the region has remained land since the end of the Palaeozoic. The main structural trends which controlled sedimentation during the two eras are opposed.

The Kufra Basin has a general northeast to southwest axial alignment and forms part of the larger Nubian Artesian Basin which extends widely into Chad, the Sudan and the United Arab Republic (Figure 8). The location is remote and little known. A few exploration boreholes have been drilled in the northern extension (south Concession 71) and a number of water wells within the Nubian have been drilled in the vicinity of Kufra Oasis. Reconnaissance investigations of the surface geology have been carried out by various geologists of the British Petroleum Co of Libya, Occidental Oil Company of Libya (Fisk and Pennington, 1970) and the Oasis Oil Company of Libya. A paper by R Selley of the Oasis Oil Company on the continental Mesozoic of southern Libya is in the Press and is referred to below.

The Phase 2 Area extends into the northern part of the Kufra Basin and the records of the few boreholes drilled in this area have been examined and used in map compilations. Some test drilling as part of the current exploration programme is projected but will not be commenced prior to the completion of this report. The following discussion of the Kufra Basin must be regarded as a preliminary outline to form the basis for localised, more detailed investigations to follow.

4.2.1 Palaeozoic Formations

Palaeozoic formations crop out against the Uweinat massif and on the northern and western margins of the Kufra Basin where they form a series of inward dipping cuesta-like ridges (Figure 7b). There is a gap in the boundary outcrops to the northwest which is covered by the Rebiana Sand Sea and subsurface information indicates a lobe-like extension of the Basin with shallow Palaeozoic subcrop below thin marine Upper Cretaceous and sporadic continental Mesozoic formations. The latter are regarded as continuous with the Nubian which thus extends into the Sirte Basin in a neck between opposing Palaeozoic outcrops or high level subcrops. The sections shown in Figure 7a extends along this line.

4.2.2 Nubian Sandstone

The Mesozoic sediments in the Kufra Basin are commonly referred to as Nubian Sandstone although Klitzsch has suggested Messak Sandstone as a local formation name. The former title will be used in this Report.

The Nubian Sandstone Series unconformably overlie Upper Palaeozoic strata in the main Basin and northwards into the Sirte Basin pass beneath marine Upper Cretaceous strata. The Series is largely unfossiliferous other than for obscure trace fossils, plant remains and freshwater gastropod shells. None of those fossils can delimit the age narrowly and the Series could conceivably range in age from the Upper Palaeozoic to the Upper Cretaceous although it is generally considered to be mainly Lower Cretaceous.

The Nubian Sandstone shows rapid lateral facies changes and Selley (op. cit, 1974, in press) recognises seven major facies, which are as follows.

1 Conglomerate facies (shrouding pre-Nubian floor with variable relief

2 Medium sandstone facies (? aeolian)

3 Coarse sandstone (braided alluvium)

4 Medium sandstone and shale facies (meandering alluvium)

5 Mudstone facies (playa lake)

6 Limestone facies (lacustrine)

7 Coarse sandstone and mudstone facies (playa: braid association)

The distribution of these various facies is unknown but would clearly have considerable hydrogeological significance. The wells drilled in the Nubian at Kufra Oasis are reported (Pallas, 1974) to have penetrated 850m of predominantly unconsolidated sand with some thick intervals of interbedded silt and clay, and smaller amounts of sandstone, siltstone and gravel. Some structural data is shown on a map by Fisk and Pennington (op. cit.) based on data collected in a series of traverses across the Libyan sector of the Kufra Basin. Dips are shown to be less than one degree except in the vicinity of the Palaeozoic formations' outcrop where they may rise to three degrees. In the southern Phase 2 Area, the Nubian has been penetrated in wells A1 and D1-71 but recorded lithological information is small. At A1-71, 790 feet of Tertiary sediments are underlain by some 2000 feet of reportedly Nubian sandstone which in turn overlie Silurian shales. At D1-71, the Tertiary and Nubian are not differentiated and shales, probably Silurian, occur some 2400 feet below ground level.

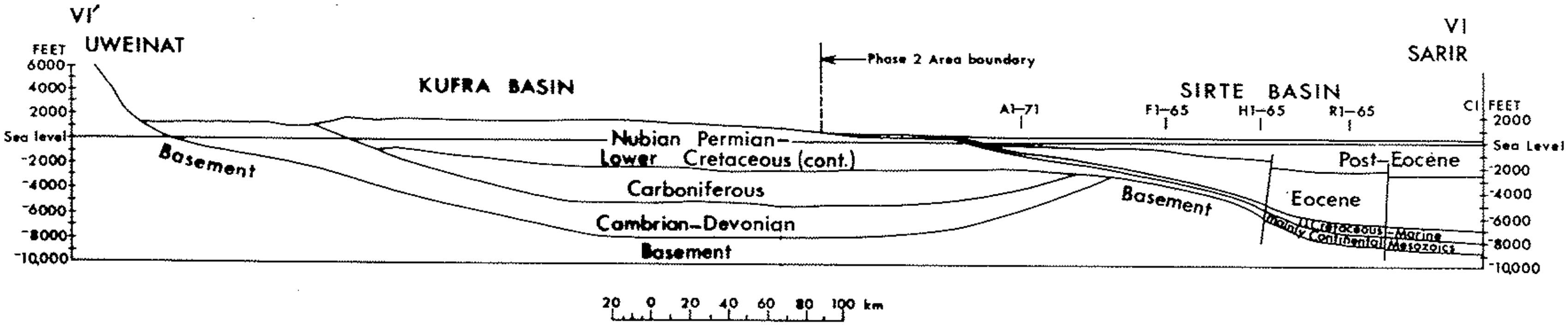
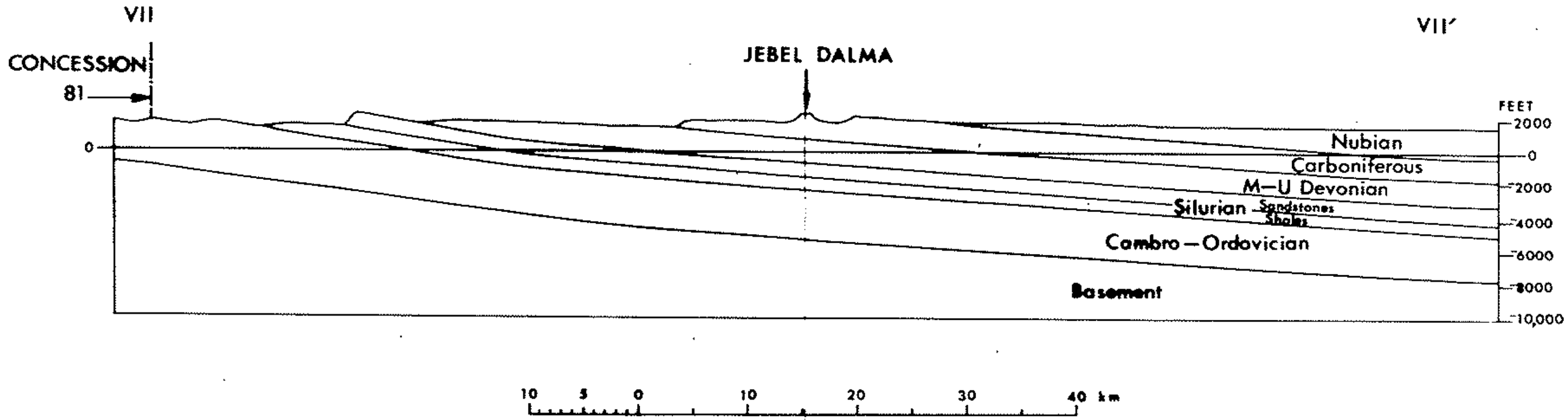


Figure 7a V1-V1[1] Schematic geological cross-section from Sarir to Uweinat



7b V11-V11[1] Sketch geological cross-section across northern margin Kufra Basin.

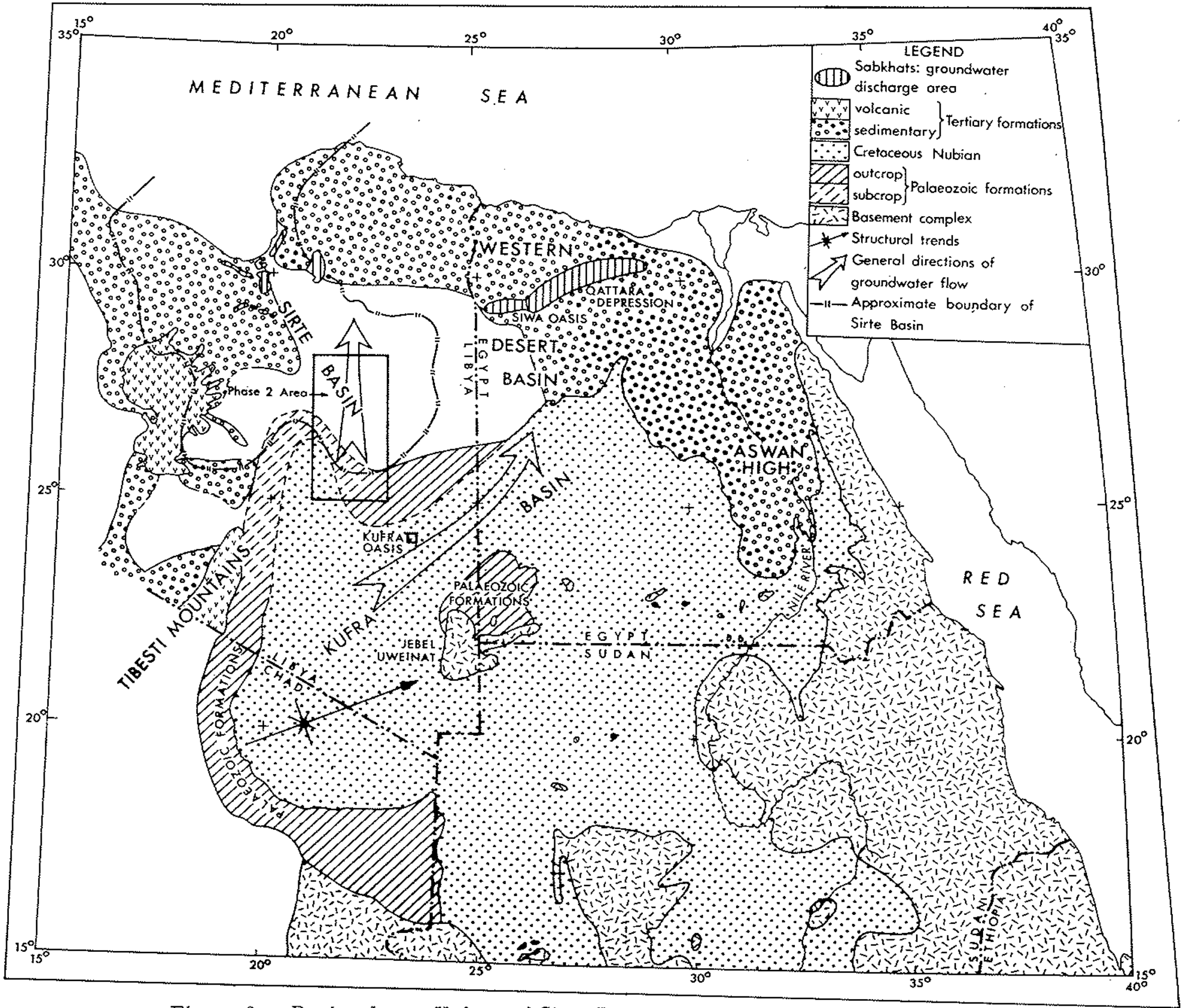


Figure 8. Regional map Kufra and Sirte Basins showing general directions ground water flow in Nubian and Post-Eocene aquifers.

TABLE 1

GEOLOGICAL SUCCESSION IN THE KUFRA BASIN

Age	Formation Name (Approximate maximum thickness in central basin)	Lithology and Depositional Environment
Recent/ Pleistocene	100m	Sand dunes, fossil soils and sabkah deposits.
Lower Cretaceous	Nubian Sandstone (900m)	Mainly cross-bedded sandstones, subordinate shales, conglomerates etc. (fluvio-continental and limnic sediments)
Carboniferous	800m	Continental sandstones and variegated shales (marine in S.W. and S.)
Devonian	(i) Tadrart Sandstones (100m) (ii) Sandstones and Siltstones (200m)	Massive, continental cross-bedded sandstones with fossil plants and well-bedded silty sandstones (marginal marine)
Silurian	(i) Tanezzuft Shales (ii) Acacus Sandstones (90m)	Sandstones, marine with fossils. Shales dark and silty with fossils.
Cambro-Ordovician	Gargaf Group (700m)	Cross-bedded sandstones and some silty shales (continental/marginal marine)
Pre-Cambrian	Basement	Folded metamorphic and granitic igneous rocks

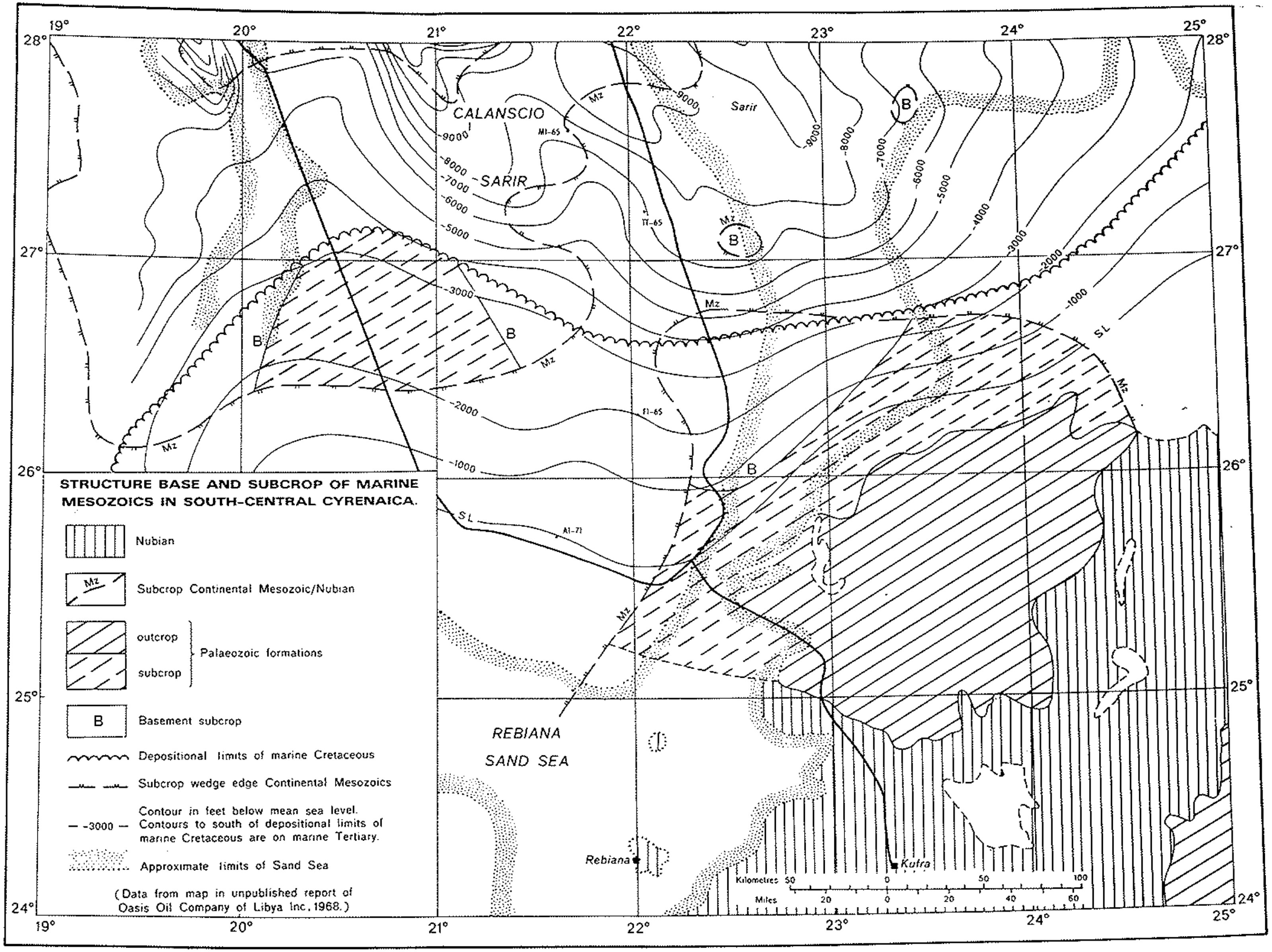


Figure 9. Structure base and subcrop of marine Mesozoics in south-central Cyrenaica.

4.3 Sirte Basin: Structure and Stratigraphy

The Sirte Basin developed in late Mesozoic and Tertiary times with subsidence initially related closely to block faulting. Faulting is most pronounced in the basin to the north of 27°00'N which is sometimes referred to as the mobile section. In Early Tertiary times, the sea transgressed far to the south of the main basin and may have reached the Niger Basin, although Desio (1971) considers it unlikely. Tertiary formations, both marine and continental, overlap the Kufra Basin northern margins and extend eastward into the Western Desert Basin.

In the Sirte Basin sedimentary succession, lithofacies was most variable in Upper Cretaceous times and closely related to structural influences with bituminous shales forming thick sequences in the grabens, and thinner reef sediments on the higher horst blocks. Differential subsidence continued into the Tertiary but the tectonic effects are reduced and the formations become more uniform, with changes occurring on a more regional scale. Faulting was commonly repetitive and progressively reducing.

The formations of particular hydrogeological interest in the Phase 2 Area are the Post-Eocene and the Nubian. The Nubian or Continental Mesozoic (regarded here as equivalent) below the Sirte Basin occurs mainly at too great depths to be of practical significance hydrogeologically and the same consideration probably applies to the pre-Nubian formations of the Kufra Basin. Nonetheless, a general understanding of the full geological succession and events within the Sirte Basin is necessary for the proper understanding of and the possible inter-relationships between the two major aquifer systems.

The full geological succession of the southern Sirte Basin is shown in Table 2 with fuller details of the Post-Eocene succession in Table 5.

4.3.1 Palaeozoic Formations

These mainly include quartzitic sandstones of Cambro-Ordovician age which form thin residuals overlying the uplifted Basement areas and increase in thickness away from them (eg 4529' at A1-71; 3560' at A1-81). The residual occurrences on the eroded 'highs' generally show considerable post-depositional alteration in consequence of repeated erosion and chemical weathering (Hea, 1971). The alterations serve to distinguish the sandstones from the overlying continental Mesozoic sandstones.

4.3.2 Mesozoic Formations

The Palaeozoic sediments were passive elements in the development of the Sirte Basin. The Mesozoic include both passive and active elements and relations are consequently complicated. They can be subdivided broadly into two units, the upper being mostly marine and more definitely Upper Cretaceous in age, the lower being mainly continental and of less certain age. It is generally referred to as Continental Mesozoic.

4.3.2.1 Continental Mesozoic Formations

These are sandstones which may range in age from Upper Jurassic to Early Cretaceous and in part at least must be contemporaneous with the Nubian Sandstone Series of the Kufra Basin. They are sometimes referred to as the Basal or Sarir Sandstones. They were subjected to several periods of erosion and chemical weathering prior to burial by the sediments of the Upper Cretaceous marine cycle. The upper horizons may locally have been reworked and partially incorporated into the overlying Transgressive Series. Alteration is much less marked where they occur away from the Tibesti-Sirte Basement uplift. The continental Mesozoic sandstones are generally unfossiliferous which makes precise dating difficult. The Basal Sandstones in the Sarir Field area have angiosperm pollen at a low level which dates them as not older than the Albian - uppermost Lower Cretaceous (Gillespie and Sanford, 19?).

4.3.2.2 Upper Cretaceous (marine)

(a) Transgressive Series. This series consisting predominantly of anhydritic shales and some sandstones is of variable thickness and generally rests unconformably on the older Continental Mesozoic sandstones, although locally deposition may well have been continuous.

(b) Upper Cretaceous Shales. These shales contain marine fossils and show a more regular distribution than the older sandstones. In common with the overlying Tertiary formations, thickness increases towards a central north-south axial zone through the Sirte Basin.

Figure 9 shows the depositional limits of the marine Cretaceous and contours on the surface below. The marine Cretaceous variably overlies Basement rocks on Palaeozoic Mesozoic sandstones. The subcrop is shown on the map and details of thicknesses of the marine Upper Cretaceous and the older, continental Mesozoic sandstones, where present, is tabulated (Table 3) at a number of sites in the Phase 2 and marginal areas.

TABLE 2

GEOLOGICAL SUCCESSION OF THE SOUTHERN SIRTE BASIN (south of latitude 28°00'N)

Era	Age	Formation	Thickness (general range in feet)	Lithology
TERTIARY - QUATERNARY	Recent	-	0-300	Windblown sands, calcretes, fossil soils
TERTIARY - QUATERNARY	(iii) Post-Middle Miocene (PMM) (ii) Lower and Middle Miocene (LMM) (i) Oligocene	Calanscio - -	500-3000	Mainly unconsolidated sand interbedded with clays and more locally calcareous sandstones grading to sandy carbonates
TERTIARY - QUATERNARY	(iii) Upper Eocene	-	200-380	Limestones and dolomites, some marls and shales
TERTIARY - QUATERNARY	(ii) Middle Eocene	-	700-1100	Nummulitic and argillaceous limestones, some marls and calcareous sandstones
TERTIARY - QUATERNARY	(i) Lower Eocene	-	800-1600	Interbedded dolomites and anhydrites
TERTIARY - QUATERNARY	Palaeocene	-	500-2000	Carbonates and some shales
UPPER MESOZOIC	Upper Cretaceous	(ii) U. Cretaceous Shales (i) Transgressive Series	70-1500	Marine shales Anhydritic shales and some sandstones
	Post Nubian Unconformity			
UPPER MESOZOIC	Continental Mesozoic (= ? Nubian)	Sarir or Basal Sandstones	0-2500	Sands and sandstones, sometimes shaly and locally interbedded with shales and sandy mudstones and siltstones
	Hercynian Unconformity			
PALAEOZOIC	Undifferentiated Palaeozoics	-	0-450	Quartzite sandstones, siltstones and micaceous shales
	Caledonian Unconformity			
PALAEOZOIC	Cambro-Ordovician	Gargaf Group	0-3800	Quartzites and quartzitic sandstones
	Pre-Cambrian	-	-	Folded metamorphic and mainly granitic igneous rocks

TABLE 3

MESOZOIC FORMATIONS IN THE SOUTHERN SIRTE BASIN

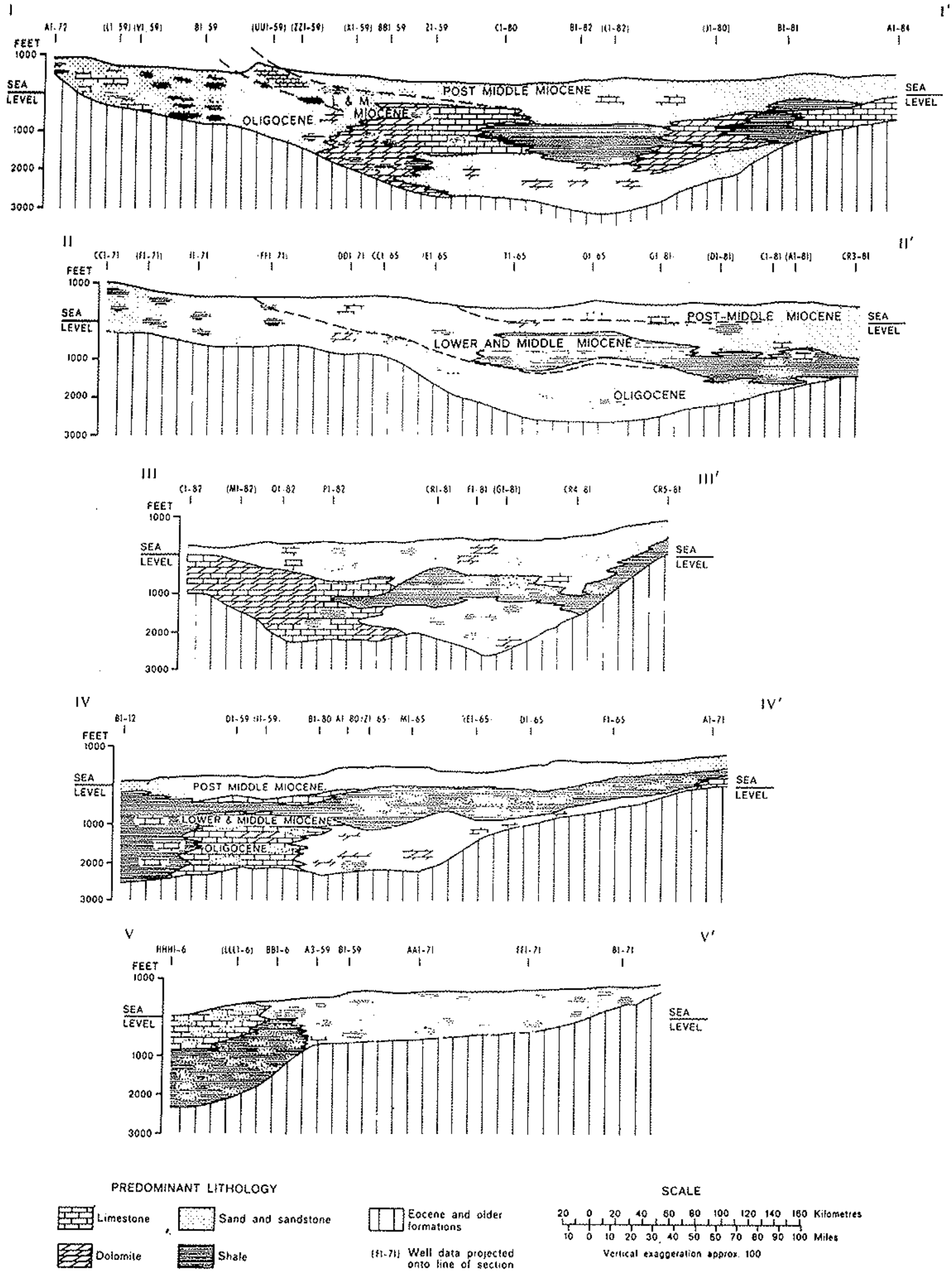
1	2	3	4	5		6	7	8
A1-65	486	-6694	995	0		Pre-Mesozoic metasediments		
A2-65	456	-6990	706	0		" " "		
D1-65	568	-3552	602	140		" " "	3,500 NaCl	973
E1-65	527	-6548	1066?	1457?	(i)	Basement	12,600 NaCl	842
F1-65	682	-1988	89	?	(ii)	Palaeozoic Sandstones?		
G1-65	536	-7139	788	1432	(iii)			554
H1-65	588	-4132	275	0		Basement	2,500 NaCl	774
Gla -65	383	-8084	543	536		Basement		729
N1-65	332	-8555	897	2061+		?		
P1-65	535	-5626	536	1960		Basement	30,800 NaCl	778
X1-65	482	-7871	1286	124	(iv)	Basement		
Y1-65	358	-8393	1515	320		Basement	215,000	622
L1-65	325	-8662	945	502		Basement		
AA1-65	312	-8276	845	0		Basement		
CC1-65	611	-3635	72	956	(v)	Basement	2,340	
DD1-65	341	-8665	995	821+		?		
EE1-65	358	-8958	1111	598+		?		733
FF1-65	308	-8224	818	0		Basement		
D1-80	182	- 13305	3800			Hole penetrates Basal Sands		
A1-81	663	-2743	636	110		Palaezoic sandstones		
B1-81	466	-4332	488	655		Basement	3,500 NaCl	
C1-81	604	-3899	584	0		Basement		
D1-81	692	-3626	285	470		Palaeozoic		
E1-81	738	- 933	325	72		Palaezoic		
F1-81	456	-6964	924	68		Basement	130,350	
G1-81	459	-7916	993	965		Basement	113,000 NaCl	
C1-71	691	-1964	120	158	(vi)	Basement		
S1-71	777	-2876		160?	(vii)	Basement		

COLUMNS

1. Well site
2. Ground elevation in feet amsl.
3. Base marine Upper Cretaceous in feet below sea level
4. Thickness in feet marine Upper Cretaceous
5. Thickness (continental) Mesozoic sandstones
6. Formation below Mesozoic sandstones
7. TDS/Salinity (ppm/ppm NaCl) of formation water in Mesozoic sandstones
8. Fresh-water head (from drill stem pressure measurements) in Mesozoic sandstones in feet amsl.

NOTES

(i) Basal sands very shaly and Oasis put base much lower
(ii) B.P. show 1616' of sandstones referred to as Cambro-Ordovician. Oasis show marine Mesozoic overlying continental Mesozoic.
(iii) B.P. show 1432' of sands overlying Basement. Oasis place marine Cretaceous deeper.
(iv) Oasis include thin basal sands with marine Cretaceous
(v) Oasis include basal sands in marine Cretaceous as very shaly
(vi) Oasis show marine Cretaceous on Basement
(vii) Base of marine Cretaceous from Oasis map which shows overlying Basement.



After Wright and Edmunds, 1969.
Institute of Geological Sciences.

Figure 10. Cross-sections through the Post-Eocene succession.
(Lines of section shown in Figure 4).

These details have been abstracted from log records of B. P. Exploration Company of Libya Ltd.

A discrepancy is apparent between the depositional limits of the marine Cretaceous on Figure 9 and the geological section in Figure 7a. The latter shows marine Cretaceous extending south of A1-71. The pre-Tertiary formations to the south of H1-65 along the line of the section become progressively thinner southwards and more sandy and of uncertain stratigraphic correlation.

4. 3. 3 Tertiary Formations

4. 3. 3. 1 Palaeocene/Eocene

These are marine sediments, predominantly carbonates. There is a marked unconformity with pronounced lithological changes between the Eocene and Post-Eocene Formations throughout the Sirte Basin. The Upper Eocene is recognised throughout the Phase 2 Area but farther east in Concession 81 appears to be absent and the uppermost horizon recognised is the Middle Eocene.

4. 3. 3. 2 Post-Eocene (Oligocene, Lower and Middle Miocene, Post-Middle Miocene)

The Post-Eocene Formations in the southern Sirte Basin which includes the Phase 2 Area are mainly continental to subordinate marine. In the northern Sirte Basin which includes the Phase 1 Area these environmental relations are generally reversed. The associated lithological changes are from a predominantly sand-clay sequence in the southern basin (Phase 2) to a sand-clay-carbonate sequence in the northern (Phase 1). The general relations are shown in the geological cross-sections in Figure 10. The carbonate and clay lithologies are locally fossiliferous but the sand sections generally unfossiliferous which makes precise dating more difficult.

An adequate evaluation of the stratigraphy of the Phase 1 Area has been possible. For the Phase 2, due to a general lack of fossiliferous horizons, the stratigraphy has had to be evaluated on lithological changes and on comparisons where possible with the more established boundaries in the Phase 1 Area.

4. 3. 3. 2. 1 Stratigraphy of the Post-Eocene Formations of the Phase 1 Area

Detailed descriptions are provided in the Interim (Wright, 1973) and Final Reports (Wright et al, 1974) and Table 4 is reproduced from that latter document. The Oligocene is predominantly arenaceous in the south with increasing shale content to the north. The depositional environment included both marine and non marine with the former predominating. The upper horizons (Diba Formation) are unfossiliferous but conformably overlie dated Oligocene (Arida Formation) and are overlain by dated Lower Miocene of the Marada Formation. The Marada Formation appears to disconformably overlie various Oligocene rocks in the marginal areas (Barr and Weegar, 1972) but in the Phase 1 which occurs more centrally in the Basin, the boundary appears conformable. The boundary has been traced from the type location (E3-59) along various cross-sections through the Phase 1 Area. It is not always well defined and frequently with transitional lithologies. In the south-east where the Phase 1 abuts on to the Phase 2 there is a fairly abrupt change from an arenaceous (Oligocene) to a carbonate (Miocene) sequence.

The dominantly carbonate rocks of the Lower and Middle Miocene (LMM) are of marine origin and can generally be dated firmly by fossil content. The younger Calanscio Formation of Post-Middle Miocene age is unfossiliferous, fluvio-continental in origin and has a restricted occurrence in the Phase 1 Area extending over about three-quarters of it with a boundary trending NNW-SSE. The PMM occurs in the central, topographically lower lying part of the Sirte Basin (section I-I, Figure 10). A correlation of present topography and thickness variations in the Post-Eocene sequence has been demonstrated and it is possible that the present outcrop may conform fairly closely with the original limits of deposition.

4. 3. 3. 2. 2 Stratigraphy of the Post-Eocene Formations of the Phase 2 and marginal areas

The Post-Eocene Formations of the southern Sirte Basin south of latitude 28°00'N, are mainly a sand-clay sequence. In the central axial region where the sequence is thickest (Section II-II, Figure 10), there is a broad three-fold subdivision in a vertical plane of sands - clays - sands. Westwards, the middle clay unit disappears as a prominent feature; eastward the clays overlap the lower sand unit. B. P. geologists recorded the local occurrence of Miocene fossils in the central clays and tentatively dated the underlying sands as Oligocene and the overlying sands as Plio-Pleistocene.

The present studies have confirmed the general stratigraphic significance of the main lithological subdivisions, and have proposed boundaries extending those which can be recognised in the Phase 1. The boundaries separate the broad lithologies but do not closely correspond with the most obvious lithological changes. The boundaries have been traced not only in the central basin where the triple lithological subdivision appears but also in the marginal areas where it is no longer apparent.

TABLE 4

Post-Eocene Sediments, Phase 1 Area

Age	Formation name	Lithology	Thickness Range in feet
Recent/Pleistocene	-	Surface sands, gravels and calcretes	0 - ? 100
Post-Middle Miocene	Calanscio Formation	Medium sands, some fine and coarse sands, grading to calcareous sandstones in part, with thin impersistent clay interbeds	0 - 600
Lower and Middle Miocene	Marada Formation	Dominantly limestones, sandy limestones, dolomites and clays, with evaporites; some interbedded sands and sandstones which increase in importance in the south west of the Phase 1 Area	400 - 2900
Oligocene	-	Non-Marine Facies comprising coarse sands and sandstones with interbedded clays occurs in the south west. Marine Facies comprising glauconitic calcareous sandstones, limestones, dolomites and clays with some evaporites makes up the bulk of the Oligocene	800 - 2300

Reproduced from Wright et al, 1974.

TABLE 5

POST-EOCENE SEDIMENTS, PHASE 2 AREA

AGE	FORMATION NAME	LITHOLOGY	THICKNESS RANGE IN FEET
Recent/Pleistocene	-	Surface sands, gravels and calcretes	0-100?
Post-Middle Miocene	Calanscio	Medium sands, some fine or coarse sands, with thin clay interbeds; occasional calcareous sandstone.	0-650
Lower and Middle Miocene		The Lower and Middle Miocene is predominantly clay in the central basin becoming increasingly arenaceous towards marginal areas. Details of individual zonal units are as follows:	?0-1300
	Zone 'a'	Sands and sandstones with thin clays; sandstones grading to sandy carbonates and carbonates in north-central basin.	
	Zone 'b'	Clays and sands with sandy carbonates in north-central basin.	
	Zone 'c'	Sands/sandstones grading to calcareous sandstones and sandy carbonates in north-central basin.	
	Zone 'd'	Predominantly clay in central basin interbedded with some sands/sandstones and sandy carbonates in north-central basin and sands elsewhere.	
	Zone 'e'	Transitional sand-clay sequence with sands increasing in percentage in marginal areas.	
Oligocene	-	Predominantly sand with some clays, and subordinate sandstones and sandy carbonates. Clays generally most significant in lower sequence but more evenly distributed in central basin. Sandy carbonates mainly occur in northern Phase 2. Lower clays commonly associated with fine sands/sandstones.	0-1400

The three main stratigraphic units are the Oligocene, Lower and Middle Miocene (LMM) and Post-Middle Miocene (PMM). Various subdivisions - designated zones - have been recognised in the two older units and are shown on the type section at T(T2-65) shown in Figure 11*; also on the lithological log of the exploration borehole T(Q1-65)A shown in Figure 12 which is located away from the central basin, and on two cross-sections which transect the Phase 2 Area, Figures 13* and 14*. The subdivisions are based on the correlated results of a detailed lithological evaluation of the available geophysical logs, as described in the section on methods of investigation (Section 2, this Report). The stratigraphy of the Phase 2 Area is given in Table 5. Figure 15 is a location map of the Southern Sirte Basin including the Phase 2 Area, showing sites and title of wells most of which have been referred to in the production of the succeeding maps.

4.3.3.2.2.1 Oligocene

The Oligocene is predominantly a sand-clay sequence with subordinate sandstones and sandy carbonates. The sandstones or fine sands are mainly identified by the neutron count but confirmation of cementation is sometimes provided in the Company lithological logs or indicated by the sonic log. The cement is calcareous. The samples collected in T(Q1-65)A included between 5-12% of sandstone fragments in the 10 foot sample sections between 1950 and 1970 feet bgl and between 2280 and 2360 feet bgl which suggests either thin banding or possibly weak and more diffused cementation. Lithological records generally indicate clays or mudstones and not shales.

Fossils have not been recorded in the Oligocene in the Company Logs and the Oligocene age is based on general continuity with Oligocene formations of the Phase 1 Area. The continuity is mainly apparent in the north-central Phase 2 Area (cf S1-80 which is shown on the section B-B, Figure 14* and also in Section D-D of Map Figure 4 of the Final Report on the Phase 1). The Lower and Middle Miocene in the Phase 2 is predominantly a clay sequence, locally containing diagnostic fossils. The upper boundary of the Oligocene has been taken provisionally at a sonic log change which can be recognised throughout Phase 2 in both central and marginal areas. Below the boundary, the sonic log shows a regular and more consistent form with lower transit times indicating a higher degree of compaction. In the central Phase 2 there is present a transitional passage through sandy formations which is commonly of the order of two hundred feet thick. It could be argued that the transition may be a weathering phenomenon and that the boundary might be taken more logically at the top. As against this, the more common occurrence of clays within the transitional section indicates continuity with the overlying formations and do not accord with the concept of weathering. The selected boundary furthermore appears more consistent with that in the western marginal areas in which the transitional passage does not occur.

The lower boundary with the Upper Eocene is commonly a marked lithological change from a sand-clay sequence above to a carbonate - clay/shale sequence below. The change may show some transitional characteristics in that the lower Oligocene commonly shows a significant clay content decreasing upwards; in other localities eg Q1-65, the lower Oligocene includes calcareous sandstones overlying Upper Eocene sandy carbonates.

The configuration of the base of the Oligocene is shown in Figure 16 and the tentative upper boundary in Figure 17. Both show a broad basin structure with north-south trending axis and lowest elevations between 22° and 23° East longitude. The general thickness of the Oligocene in the northern Phase 2 is in the range 900-1100 feet with some anomalous higher values in the south-east which may relate to reduced compaction as compared with more central areas in consequence of reduced clay percentages.

Sands, clayey sands and sandstones compose between 70 and 90% of the Oligocene succession over the greater part of the Phase 2 Area. Sandstones/fine sands appear to have an irregular distribution but tend to constitute higher percentages (15-30%) in the northern Phase 2. Sandy carbonates and carbonates are also limited to northern areas and the latter occur only in the central basin. Clays are mostly concentrated in the lower half of the succession except in the central basin areas where they show a more varied distribution throughout the sequence.

The depositional environment was probably continental in the main to locally marine in the north-central basin areas where glauconite has been recorded sporadically at various levels (see M1 and FF1-65 and S1-80 in Figures 13* and 14*). Lignite has been recorded occasionally, mainly in the lower levels. Lithological samples from T(Q1-05) were analysed according to the methods of Moiola and Weiser (1968) (see Appendix 4) and all crossplots occurred in the field of fluvial deposition. Glauconite is recorded only once in the Oligocene at Q1-65 and the occurrence could indicate local marine conditions having existed but may be detrital. Anhydrite has been recorded once only, also at Q1-65.

*Figures shown with an asterisk are not included within the text but folded in an end pocket.

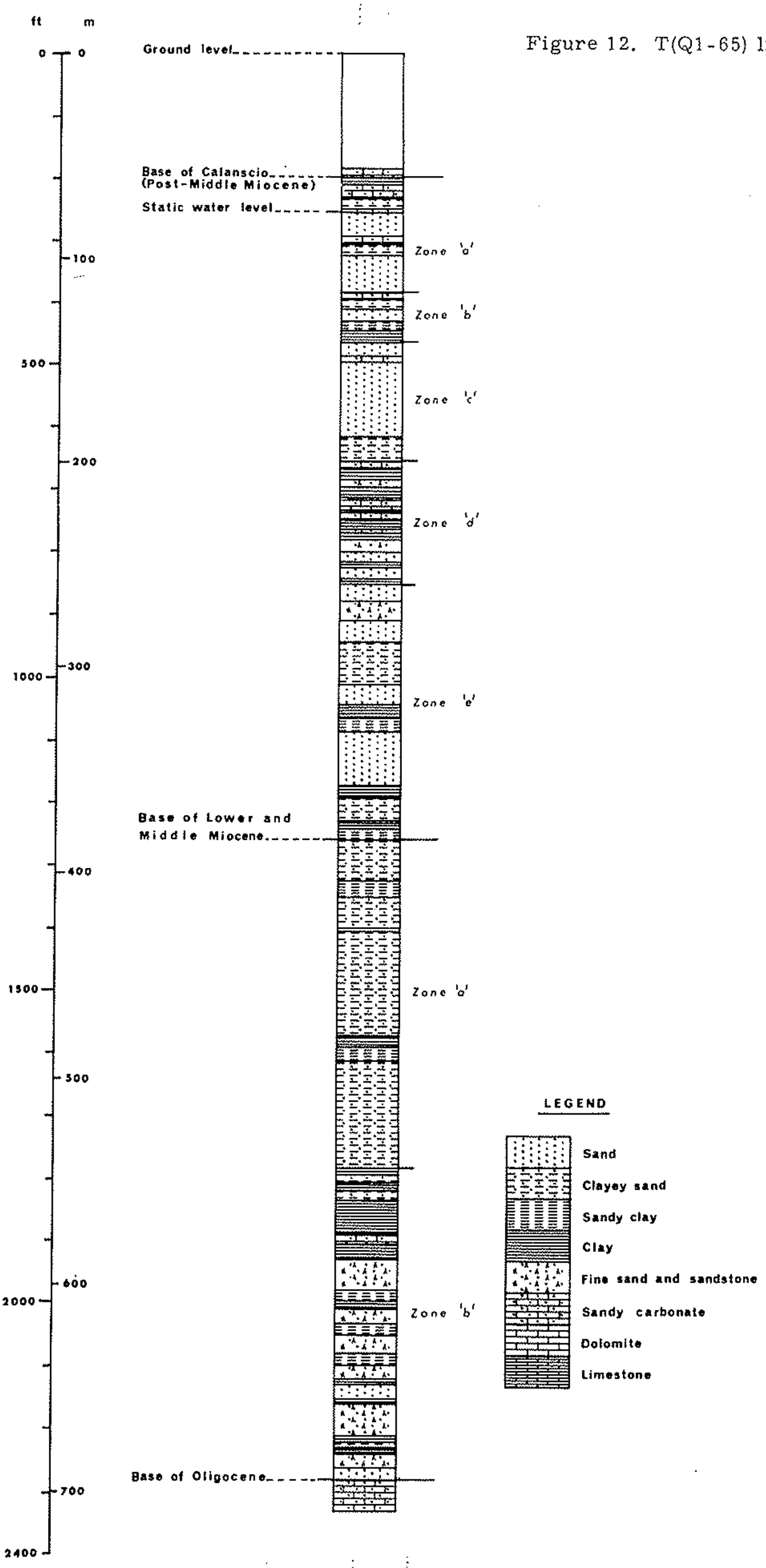


Figure 12. T(Q1-65) lithological log.

The sands are variously described as ranging from fine to coarse grained and no distribution patterns over the Phase 2 Area are apparent with the data available. Detailed cycle patterns are likewise not apparent in the vertical section sampled at Q1-65 although a general increase in average grain size occurs from lower to higher levels (Table 6). The finer sands thus occur in the lower zone 'b', Figure 12, and the feature accords with the low porosity values.

The regional occurrence of the Oligocene in areas to west and east of the Phase 2 has not been ascertained and no detailed study of the available logs in Concessions 71 and 81 have been made. The recorded outcrop of Oligocene in Waha Field (Section I-I, Figure 10) may extend to the south as tentatively indicated in Section II-II. To the east of Phase 2, the Miocene may overlap the Oligocene onto the Eocene, unless significant facies changes have occurred in both Miocene and Oligocene.

4.3.3.2.2.2 Lower and Middle Miocene (LMM)

The Marada Formation of LMM age in the northern Sirte Basin is predominantly a carbonate - subordinate shale/clay sequence which in the Phase 1 Area includes some interbedded sands and sandstones increasing in importance to the southwest. The boundary with the overlying Calanscio Formation of Post-Middle Miocene age (PMM) is commonly a marked lithological change from a carbonate to an unconsolidated sand sequence but the distinction is less well marked where the LMM includes sandy formations in the upper levels. The distinction is sustained however by the common presence in the LMM of more prominent clay horizons with a higher gamma count as compared with the clays in the Calanscio Formation, and occasionally also by changes in the sonic or resistivity log characteristics indicating higher compaction of the LMM.

The lower boundary of the Calanscio Formation has been traced southwards across the Phase 2 Area and the configuration shown in Figure 18 is based mainly on data described in an IGS unpublished Report (Benfield, 1973). The contours in Figure 18 are drawn by computer techniques and differ in detail from those shown in the Report referred to.

In the north-central Phase 2 Area, the boundary is defined by significant lithological changes from sands to underlying sandy carbonates (S1-80; FF1-65 in section B-B, Figure 14*). To the south and west, the lithological changes become increasingly less marked and the boundary consequently less certain. Nonetheless there is generally an increase in clay proportions (or carbonates in northern areas) and changes in geophysical logging responses which confirm the existence of the boundary. The relations are exemplified by the logs of T(T2-65), Figure 11*. Here neither clay proportions nor gamma count are notably increased below the projected boundary but resistivity, sonic and neutron log responses show significant changes indicating among other aspects increased compaction.

The western and southern boundary outcrop is tentatively shown in Figure 18. In the Phase 1 Area, the outcrop boundary is made apparent by the difference in drainage patterns on the consolidated Miocene limestones as compared with the unconsolidated PMM sands. The lithological distinction is less well marked in the Phase 2 Area in the vicinity of the boundary outcrop and drainage patterns are probably less diagnostic, although no detailed examination of the aerial photographs has been carried out to confirm this. Boreholes west and south of the boundary in Concessions 65 and 71 are few and widely scattered but in the more northerly areas the higher levels commonly include interbedded sandy carbonates (eg T1-71) and farther south well defined clays (CC1-65), both features being more diagnostic of the LMM.

Five subdivisions of the LMM have been recognised in the Phase 2 Area. These are briefly described in Table 5 where they are listed for convenience as zones 'a' to 'e'. The subdivisions are based on lithological differences but their continuity over a large part of the Phase 2 Area suggests stratigraphic significance. Facies changes occur within the subdivisions and can be most readily appreciated by reference to the cross-sections Figures 13* and 14*. Cross-section B-B trends from north to south approximately along the line of the structural axis. Cross-section A-A trends NNW-ESE, somewhat offset from a more appropriate E-W line. The thicknesses of the various zonal subdivisions appear fairly constant over the main basin area in northern Phase 2 with those of the upper three being generally comparable. The boundary between zones 'd' and 'e' is not generally well defined. The configuration of the boundary surfaces between zones 'a' and 'b', 'b' and 'c' and 'c' and 'd' for the main basin area in northern Phase 2 are shown in Figures 19, 20 and 21.

The relations in the more remote eastern marginal areas beyond Phase 2 in Concession 81 have not been investigated in any detail during the current studies. Exploration oil wells are comparatively few. Subsurface data for areas to the north-west (F1, G1, CR1, B1-81) show the usual major three fold grouping with a well-defined middle clayey unit in which five subdivisions can be recognised corresponding to the general occurrence in the Phase 2. To east and south-east, significant modifications occur in the lithology of the

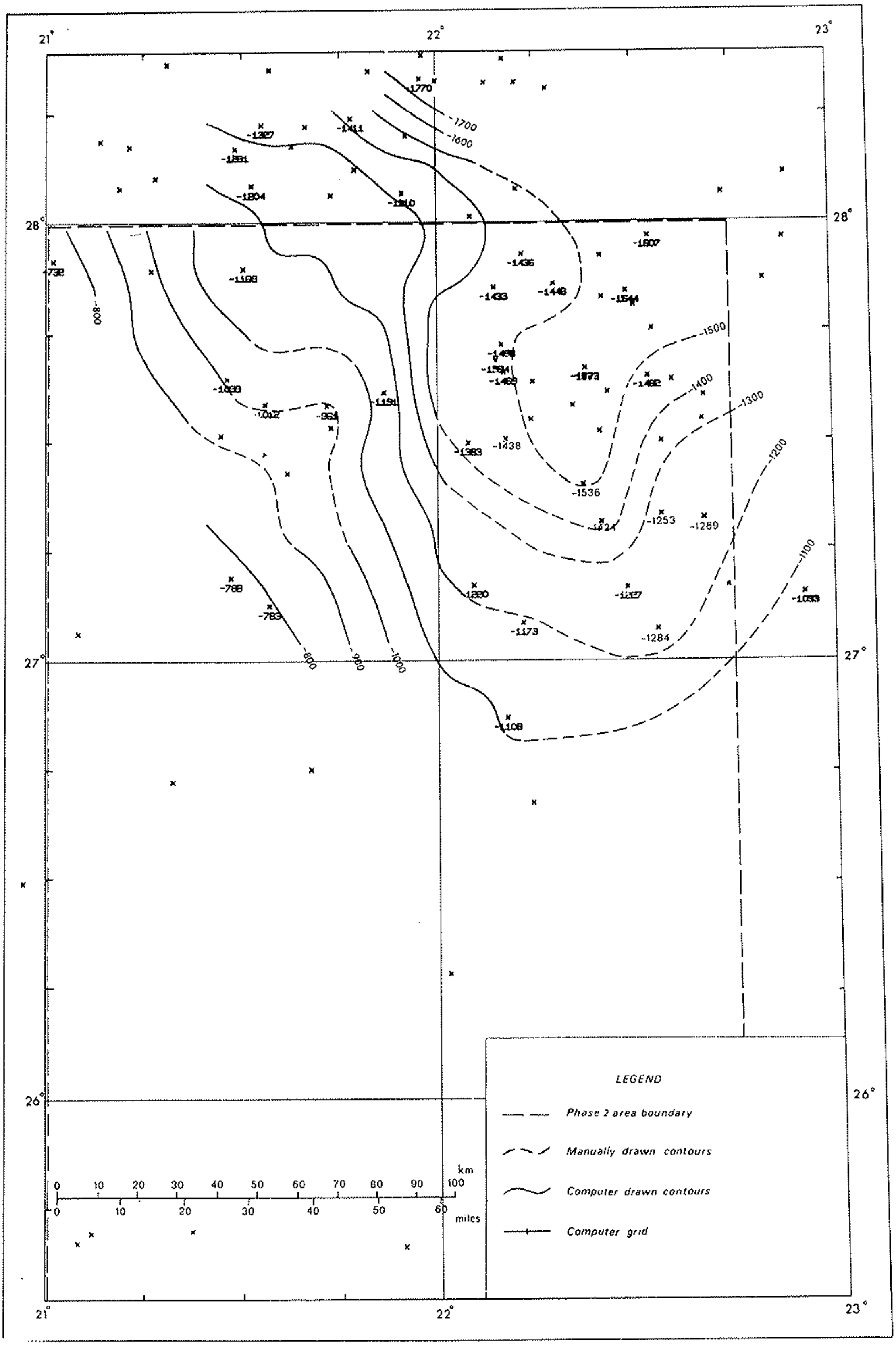


Figure 17. Base of Lower and Middle Miocene (computer plot).

TABLE 6

Selected size analysis data in Post-Eocene samples from Phase 2 test drilling sites.

	1	2	3	4	5
T(U1-65)					
1	100-500	642	285-1450	3.1	2.24-6.0
2a	500-630	347	225- 670	3.1	2.22-4.63
T(FF1-65)					
1	110-460	583	360-1150	3.51	2.41-4.58
2a	460-490	352	265-550	3.22	2.91-3.77
T(T2-65)					
1	180-390	403	280-540	2.78	2.57-3.27
2a	390-560	373	193-525	2.71	2.03-3.65
2c	690-860	325	205-595	3.22	2.15-5.13
T(P1-65)					
1	200-240	309	238-338	2.72	1.77-3.06
2a	240-390	353	296-620	2.91	2.16-3.68
2b	390-560	357	310-560	3.00	2.31-4.06
2c	560-730	246	185-320	2.43	1.78-3.50
2d	730-780	191	163-238	1.98	1.66-2.25
T(H1-65)					
1	220-250	387	380-390	1.37	1.35-1.40
2a	260-350	358	290-440	1.51	1.20-1.80
2c	380-530	239	205-300	2.09	1.75-2.20
T(Q1-65)					
2a	200-390	313	150-390	2.31	1.89-2.83
2b	390-470	206	185-240	1.89	1.72-2.14
2c	470-660	310	207-540	2.23	1.73-3.53
2d/e	660-1260	271	155-450	2.27	1.60-3.12
3a	1270-1500	402	220-540	2.95	2.02-5.82
3a	1550-1850	279	180-544	2.70	1.96-4.16
3b	1940-2360	185	135-285	2.74	2.0 -3.68

ROWS:

1. Post Middle Miocene
2. Lower and Middle Miocene) a, b etc are zonal units
3. Oligocene)

COLUMNS:

1. Section sampled in feet bgl. Not all 10 feet samples could be sieved (for full details see appropriate appendices)
2. Average D50 in microns
3. Range of D50 values
4. Average uniformity coefficient (D40/D90)
5. Range of uniformity coefficient values

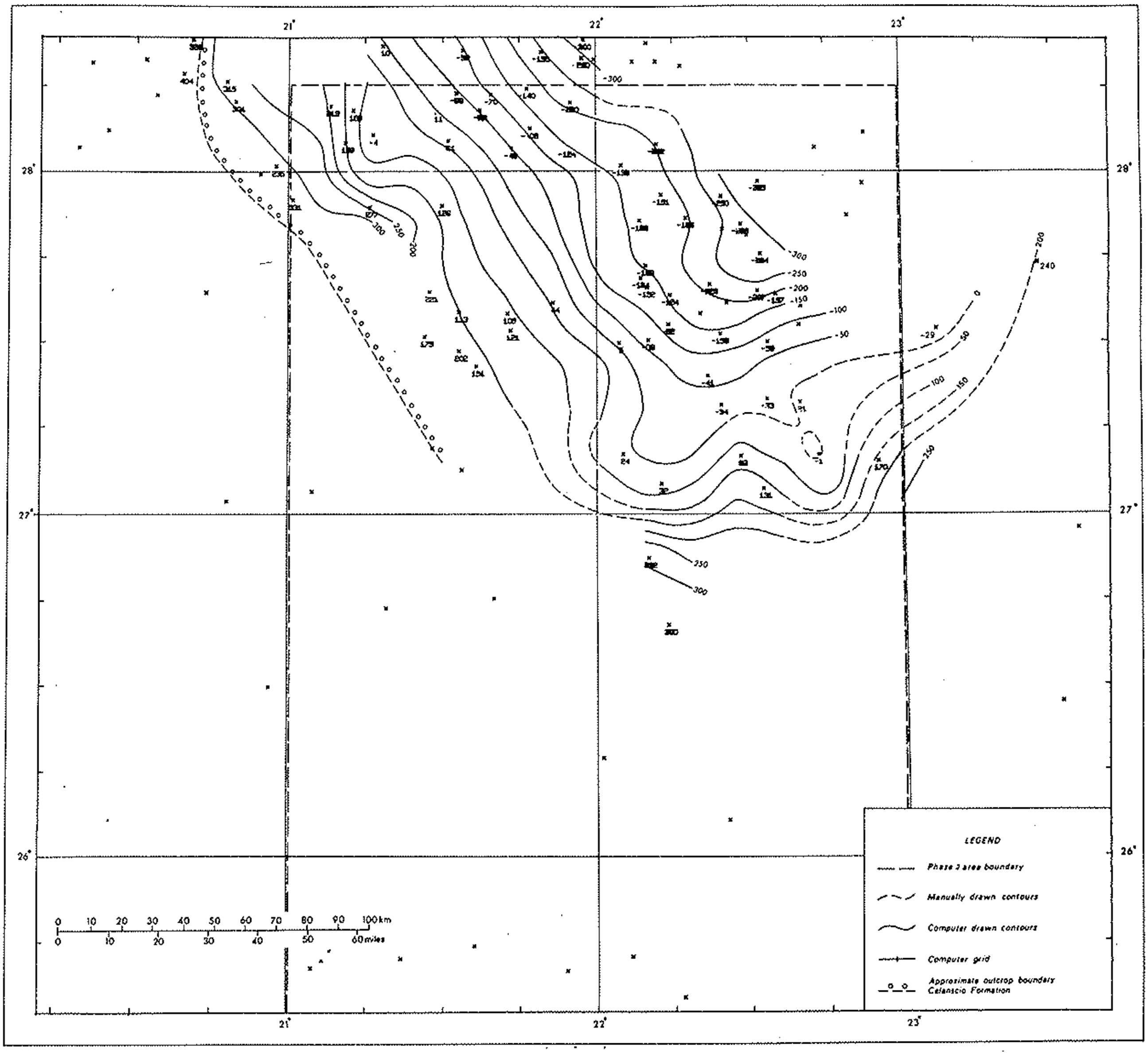


Figure 18. Base of Calanscio (Post Middle Miocene) Formation (computer plot)

Post-Eocene sequence which have not been fully evaluated. In the east-central area (cf CR3-81), the entire sequence is dominantly sandy with thin clays increasing at lower levels. To the south-east (CR4, C1-81), a thick sandy sequence above is succeeded downwards by a clay-sand sequence. Significant facies or thickness changes must be postulated for a correspondence to be established with the sequence in Phase 2. On general palaeogeographical grounds, it is thought that the lower clays/sands may be Oligocene with the overlying sand mainly LMM which would imply a significant lateral facies change from clay to sand. The assumption is very tentative and requires confirmation.

Summaries of the lithological variations in each zone are as follows, commencing from the top:-

Zone 'a' is predominantly arenaceous. Along the central axial line of the basin from north to south, the sequence shows progressive changes from carbonates and sandy carbonates grading to calcareous sandstones and sands with some interbedded clays. In marginal areas to east and west, sands predominate.

Zone 'b' : along the central axis this is a carbonate-clay sequence in the north. Carbonates rapidly phase out southwards and subordinate sands come in which develop significant proportions in the southern areas.

Zone 'c' is also an arenaceous unit interbedded with some carbonates and sandy carbonates in the north, and clays in the centre and south.

Zone 'd' is the second clay unit, with thick clays dominant in the central basin becoming interbedded with sandy carbonates to the north and with sands to the south-west and east; eventually sands predominate.

Zone 'e' is a transitional sand-clay sequence well defined in the central basin and less so in marginal areas.

At FF1-65, in the north-central basin, the three middle zones, 'b' to 'd' contain marine fossils of Miocene age. The transitional facies above and below can logically be considered as the same age. Gypsum and anhydrite are common in the clays, occasionally in thin bands, more usually dispersed. They are limited to the central basin as far south as latitude 27°00'N. Other environmental diagnostic features include glauconite and lignite/carbonaceous laminae. Significant occurrences are noted on the cross-sections, Figures 13* and 14*. The lignite or carbonaceous laminae occur in more marginal locations, mainly to the south. In one occurrence, lignite is associated with a gastropod (? freshwater) limestone.

The general characteristics of the Lower and Middle Miocene formations suggest a marine lagoonal environment in the north-central basin areas with transitions into estuarine/deltaic and perhaps fluviatile environment in marginal areas to south, west and east. The size analysis plots of the Miocene samples at T(Q1-65) fall mainly into a fluviatile environment other than three horizons each some 30 feet thick in zones 'd' and 'e'. The horizons are shown on section B-B and the occurrence in the 'transitional' zone 'e' gives some confirmation to the differentiation of this zone from the fairly similar sand sequence below which invariably plots of the fluviatile field. (see Appendix 4).

4.3.3.2.2.3 Post-Middle Miocene

The Calanscio Formation of Post-Middle Miocene age consists predominantly of unconsolidated sands with occasional thin interbeds of clay and some local occurrences of calcareous sandstones and more rarely sandy carbonates. The sands are variably described as fine to coarse, occasionally pebbly. In the analysed samples, Table 6, the sands are generally medium grained and uniform. Defined cyclic patterns are not apparent although a slight indication of two upward coarsening sequences occur in the sampled section at T(U1-65). The average grain size is appreciably coarser than that of the underlying LMM but the lower levels of the PMM are finer than the upper. This is apparent in the details from the Appendices. At T(P1-65) and T(T2-65) the section of the PMM analysed is limited to the lower levels where the average grain size is more comparable to that of the LMM.

The occurrence of the PMM to the east of the Phase 2 Area in Concession 81 has not been studied in any detail. The boundary appears to rise initially as shown in Figure 18 but farther east the increase in thickness of the high level sand horizons implies a second basin development or more probably a facies change from clay to sand within the LMM. The latter supposition is preferred and tentatively indicated in Figure 10, Section II-II.

Cross-plots of grain size characteristics indicate a fluviatile environment. Calcareous sandstones may indicate calcreted deposits which could be sheet-like, or alternatively elongated bodies developed in the vicinity of ephemeral streams. The occasional carbonate occurrences are probably lacustrine. Clays are generally sandy or silty and are likely to be of limited extent on the assumption of their being over-bank deposits. No significant distribution patterns have been recorded within the PMM. Information on the upper levels is rather

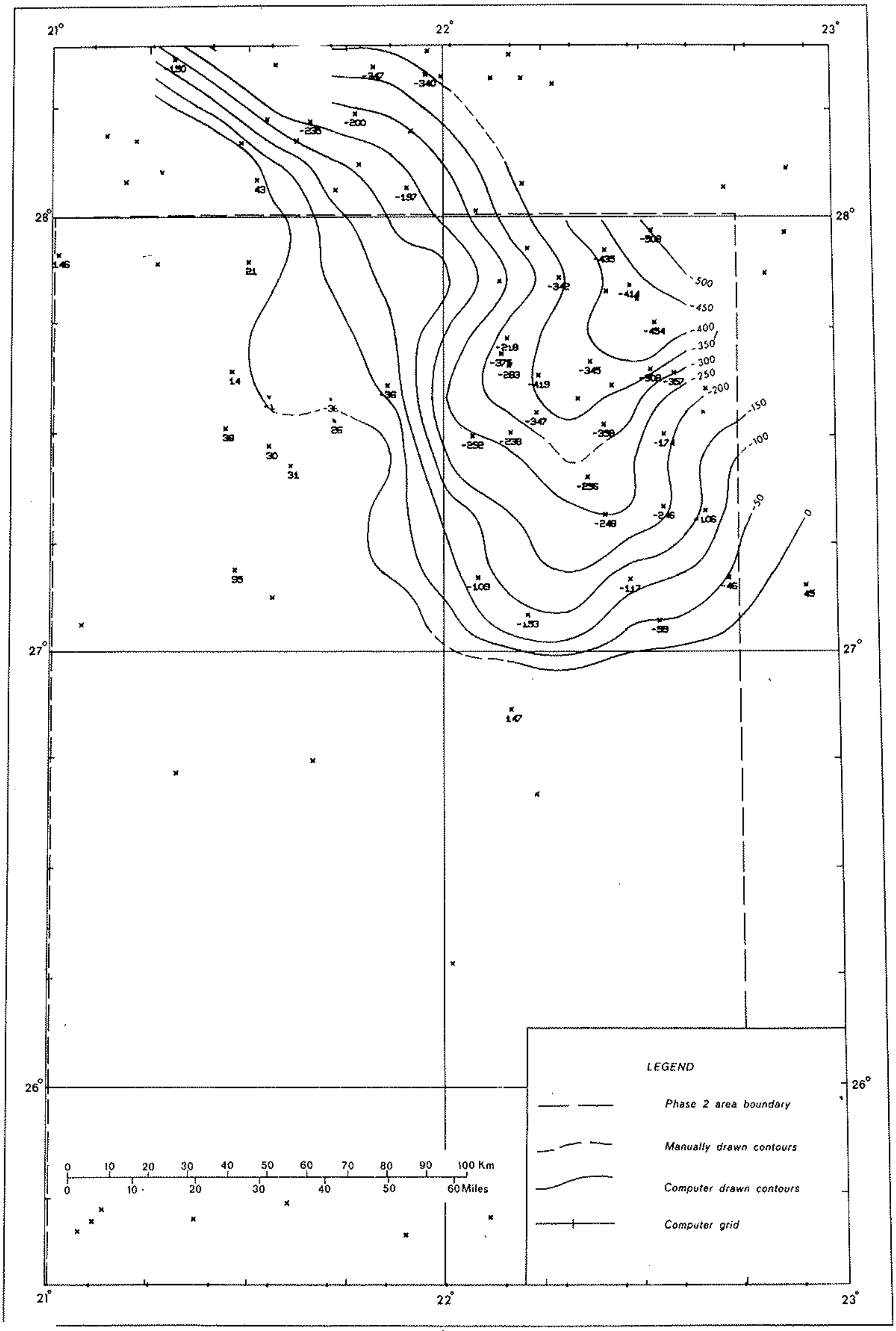


Figure 19. Base of Zone 'a' : Lower and Middle Miocene (computer plot)

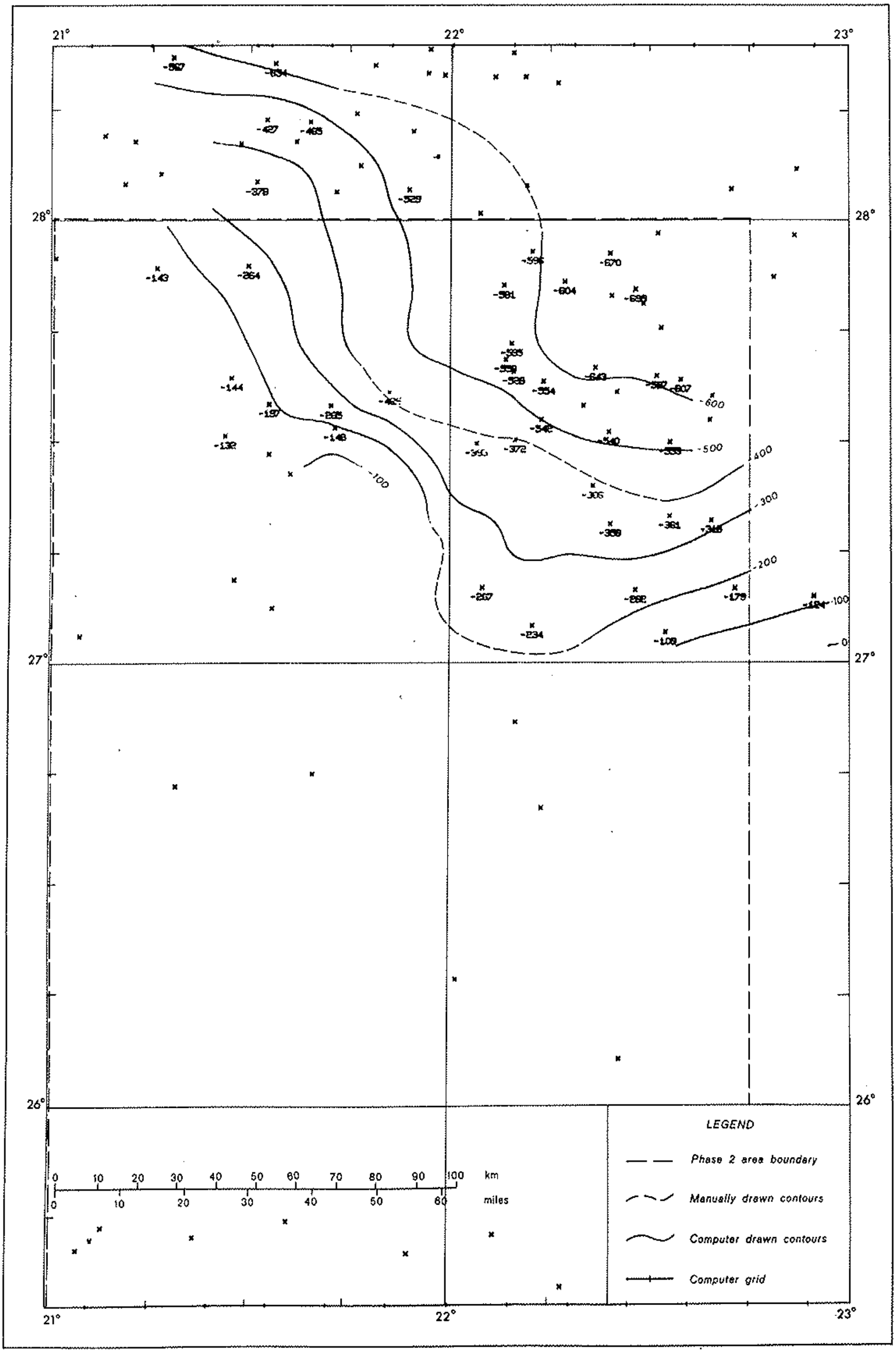


Figure 20. Base of Zone 'b' : Lower and Middle Miocene (computer plot)

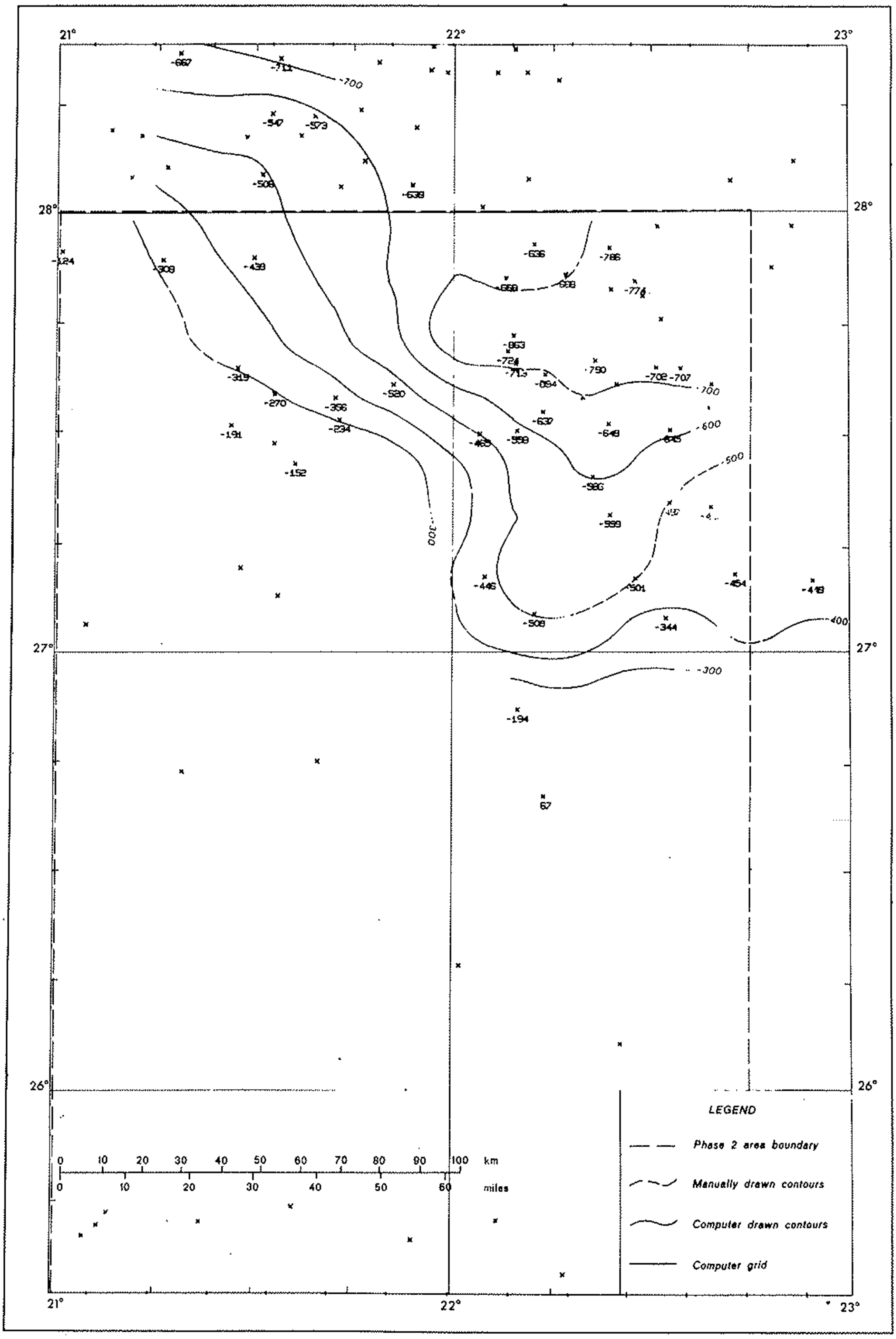


Figure 21. Base of Zone 'c' : Lower and Middle Miocene (cumputer plot)

scanty since geophysical logs generally commence at 150-200 feet below ground level and on the test sites due to lack of time, sampling has been restricted to below the water table. It should also be noted that no distinction has been made during drilling between the PMM and overlying 'recent' deposits.

4.3.3.2.2.4 Quaternary Deposits

The dunes of the Calanscio and Rebiana Sand Seas constitute the most prominent of the recent surface deposits of the Phase 2 Area. As such they represent a significant environmental change from the alluvial sequence of the PMM. North beyond the Phase 2 in the vicinity of Jaghbub (latitude 29°30'N) at the northern edge of the Calanscio Sand Sea, a continental sequence has been established - the Garet Ueda Formation, (di Cesare et al, 1963) older than the dune sands and consisting of four horizons composed of sandy clay, marly sandy limestone and limy sandy caliche and typical of a subacqueous environment, separated by three levels of aeolian sand facies. The fossils in the subacqueous deposits are of Pliocene - Quaternary forms. The relation between the Calanscio Formation and the Garet Ueda Formation has not been established but it is significant perhaps that all the analysed samples of the former appear to be fluvial. Additional information on the upper levels of the Calanscio Formation and on the occasional outcrops of calcrete, sandy limestone etc may help to clarify the position.

Desio (1928, 1971) considered that the sand seas were largely produced and accumulated in the areas in which they are found today. Original distribution is regarded as fluviatile with wind being responsible for the shape and disposition of the recent dunes. Both the Calanscio and Rebiana Sand Seas are located in extended topographic lows. The dune belt in Concession 71 to the west of Phase 2 continues the line of the valley into Marada. Occasional outcrops of sandy calcrete and marl have been noted in inter-dune areas in the vicinity of Sarir field. These may represent older wadi deposits and support Desio's opinion.

4.3.3.2.2.5 Summary of details of Post-Eocene Formations

The Post-Eocene sequence shows facies distributions related to a north-south trending basin located centrally in the Phase 2 Area. The Oligocene is predominantly a sand sequence, probably fluvio-continental to locally marine. The Lower and Middle Miocene Formations are dominantly marine clays in the north-central basin, probably grading into mixed marine, estuarine and eventually fluvio-continental in marginal areas the south, east and west. Carbonates occur to the north and sands increase towards the marginal areas, south, east and west. The Calanscio Formation of Post-Middle Miocene Age is predominantly sandy and appears to be fluvio-continental. Most recent deposits include dune sands, fossil soils, surface calcretes etc. The relations between these deposits and the Calanscio Formation have not been established but there might well be a continuous transition. Transitional facies occur between all other major stratigraphic subdivisions of the Post-Eocene and although significant facies and environmental changes have occurred, the sequence appears broadly conformable in the central basin areas. Obvious unconformities occur in the more distant marginal areas beyond Phase 2 where recent deposits for example may overlie Miocene or Oligocene formations.

Shore line locations appear likely to be closely related to the form of the structural basin with marine influence strongest in the deposits of the central axial region which at the present time also corresponds to a topographic low. Marine incursions are unlikely to have extended beyond 27°30'N latitude in the Oligocene and Miocene but with a wider east-west spread in the Miocene.

Within the southern Sirte Basin south of latitude 28°00'N, the Miocene and Oligocene Formations show the widest spread, whilst the PMM appears largely restricted to the central main basin. The Miocene may perhaps overlap the Oligocene to the east but this is uncertain and a facies change is preferred with both Formations being present. Present outcrop of the PMM may not be very different from the original limits of deposition with contemporaneous erosion of older Miocene in the marginal outlying areas. The drainage patterns overlying the Miocene outcrops could be a combination of ancestral and later trends related to a similarly located topographic base level. The absence of prominent drainage patterns in the Miocene to the south could be the effect of the recent arid cycle obliterating patterns within largely unconsolidated material. Information on these aspects require a detailed geomorphological study which would consider drainage patterns and base levels of erosion and might make use of heavy minerals distribution.

5. HYDROGEOLOGY

Within the Phase 2 Area, the aquifers which merit detailed study by virtue of containing accessible fresh water include the saturated formations of the Post-Eocene and the Nubian Sandstone. The Post-Eocene has a maximum saturated thickness of about 2800 feet and the Nubian Sandstone about 2000 feet. These figures refer to their occurrence within the Phase 2. The Nubian Sandstone is underlain by older Palaeozoic sandstones on which hydrogeological information is negligible. It is probable however that these older compacted and cemented sandstones would prove too poorly permeable to be productive even if other considerations of depth or water quality were favourable. The Nubian Sandstone is mainly significant in the Kufra Basin which extends into a limited section of the Phase 2 Area. Continental Mesozoic sandstones equivalent at least in part to the Nubian extend northwards below the Sirte Basin, and although the contained water is generally saline or the formations too deep to be of practical significance, a brief discussion of the hydrogeological relations is necessary for a comprehensive understanding of the Nubian aquifer and possible inter-relationships with the Post-Eocene aquifer system.

The saturated Post-Eocene and Nubian Sandstone Series include interbedded clays or shales and the aquifers are in consequence complex bodies ranging from unconfined to fully artesian. Under natural flow regimes, vertical components of hydraulic head do not appear to be very significant within each aquifer system. A significant head difference between the Nubian and Post-Eocene does frequently exist where the two occur together.

Radio carbon dating on water samples from the Nubian at Kufra Oasis and from the Post-Eocene at various scattered localities in the Sirte Basin in both Phase 1 and 2 Areas has shown fossil ages. The Nubian groundwater ages are mostly in a range 2400-4400 years. Groundwater in the Post-Eocene have shown a wider age range between 8000-40,000 years+ (see Final Report, Wright et al, 1974). The range has significance with younger water overlying older and associated with patterns consistent with recharge along drainage lines. These results coupled to data on climatology and surface terrain indicate little likelihood of significant current recharge over the main outcrop areas of the two aquifer systems. Some recharge may be occurring in the vicinity of upland areas such as the Tibesti Mountains or the Haruj Al Aswad but the remoteness of these locations renders the concept of little practical significance. Proposed developments can be therefore considered in effect as 'mining operations'.

Water quality in the Nubian aquifer in the Kufra Basin appears to be very good. Quality is more variable in the Post-Eocene aquifer system. Resources in both aquifers are undoubtedly of a high order although there are likely to be considerable development problems related principally to the remote locations where development is warranted. Abstraction from the Nubian has been in progress for some years. The quality of the discharge has been maintained but there are some anomalous aspects of hydraulic response which are currently under consideration by the Kufra and Sarir Authority. In this Report, the Nubian will be considered in its more regional aspects and will exclude the localised development problems of the Kufra Oasis well fields. For information on these aspects, reference should be made to various reports by Messrs Tipton and Kalmbach.

Development from the Post-Eocene aquifers in the Phase 2 Area has been limited to abstraction at the Sarir Oil Field in relation to Company operations, and at Tazerbo Oasis in relation to small scale agricultural and domestic requirements. At Sarir a small number of wells have been producing more or less continuously for several years at a few hundred gallons a minute without significant change in water quality.

5.1 Regional Flow Patterns in the Nubian Sandstone Aquifer

Figure 22 is a map of the piezometric surfaces within the two aquifers in Central and Southern Cyrenaica. Figure 23 shows the Post-Eocene piezometric map of the Phase 2 and marginal areas. Data on the Nubian in the main Kufra Basin is limited to observations in the vicinity of Kufra Oasis and at a few other scattered locations in the same general area. Data on the piezometric heads within the Continental Mesozoic sandstones within the Sirte Basin to the north are derived from drill stem tests carried out by British Petroleum Co. (Libya) Ltd in the course of their exploratory operations. Jenkin's (B.P. Co. of Libya Ltd., unpublished Report 1967), discusses the fluid mechanics of the sandstones on the basis of hydraulic heads expressed as an average value between a fresh water and formation fluid head. In the present discussion, the piezometric head is considered to be more realistically expressed as the equivalent fresh water head which is the height of fresh water above the level at which the pressure was measured and corresponding to this pressure. The values show some anomalies but a consistency in the region to the south of latitude 28°oo'N indicating probable hydrostatic continuity with gradients to south-east and east. Data from areas farther north in Concessions 59 and 80 suggest a hydraulic discontinuity

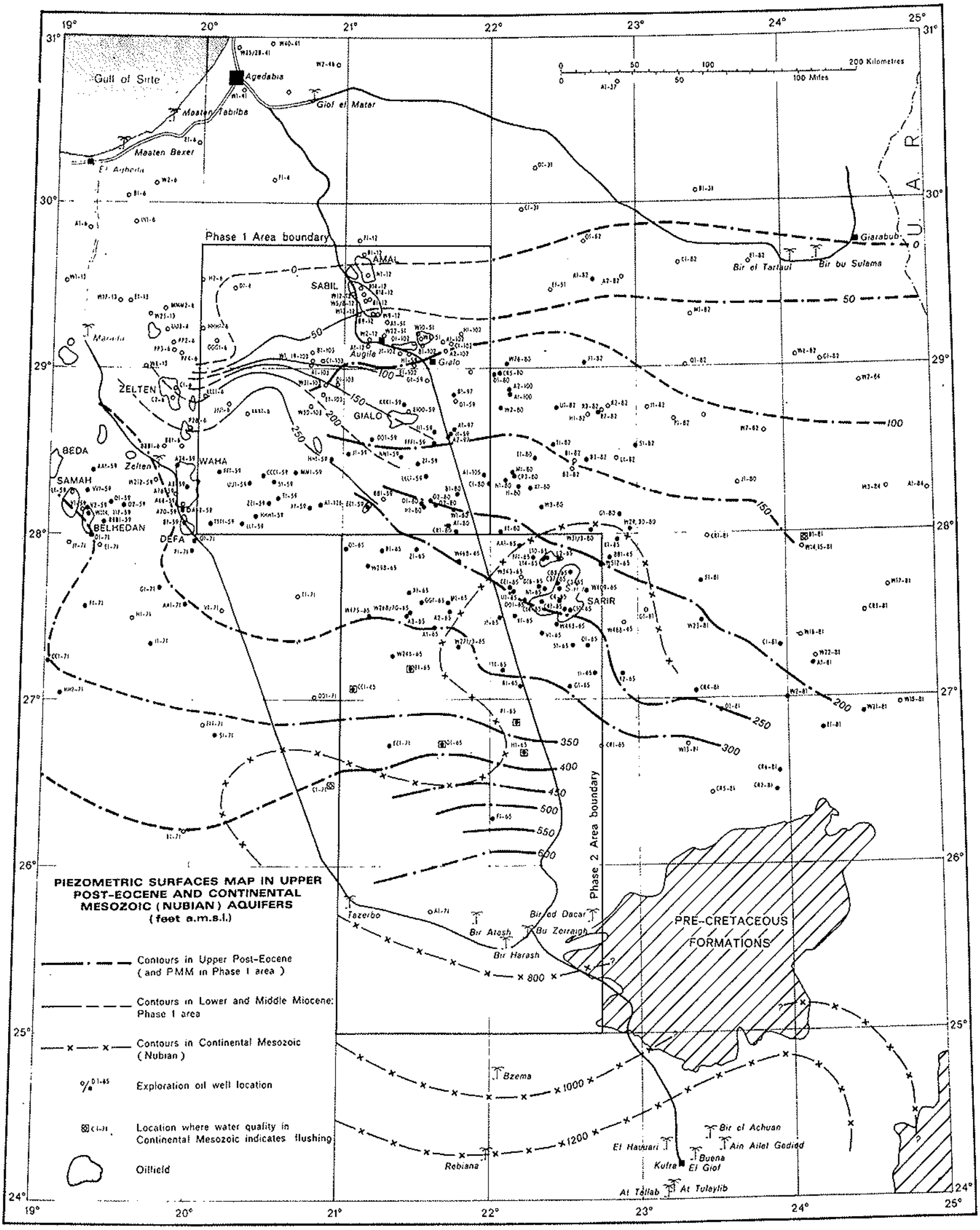


Figure 22. Piezometric surfaces map in upper Post-Eocene and Continental Mesozoic (Nubian) Aquifers.

with areas to the south, the result either of faulting or wedging out of the sandstone against basement barriers.

Under natural flow conditions, some discharge is occurring by evapotranspiration at Kufra and other oases in this area. An upward component of flow consequently exists but the head differential as measured in Kufra between the deep and shallow wells is generally less than one metre and decreases rapidly away from the oasis. The main gradients are therefore as shown in Figure 22 with two divergent trends. The main northeasterly trend is continued within the U.A.R. (Figure 8) curving northwards towards the zone of discharge in the belt of oases and sabkhats from Kharga to Quattara and Siwa (Himida, 1970; Hellstrom 1940). Whether this gradient is entirely transient and controlled by ancestral recharge with current discharge or whether there is some recharge in the Tibesti Highlands effecting some control, is not known, and cannot be readily surmised.

The gradient to the northeast in the general vicinity of Kufra Oasis is approximately 1 in 3000. The diverging northward trend appears to be shallower. This latter trend may be related in part to groundwater discharge from the northern oases of Bzema and Buzerraigh but seem likely to have a more significant remoter control, probably as indicated by the piezometric map via the Sirte Basin into the main Nubian Basin of the U.A.R. In considering the groundwater trends in the Mesozoic sandstones of the Sirte Basin, the wedging out or discontinuity of the sandstones over the basement high to the west of the 800 feet contour shown must be noted. Since no recharge can be occurring and considering the stratigraphic relations, these gradients would seem to be controlled by flow through the main Nubian aquifer system.

The Continental Mesozoic sandstones were presumably saturated with sea water in the Upper Cretaceous marine incursion. The presence of fresh water in the more southerly locations (Figure 22) presupposes flushing by fresh water, presumably from the Nubian outcrop to the south, since the overlying Tertiary formations include impermeable shales. Consideration of the necessary gradient forces might give indications of ancestral elevations of the Nubian piezometric surfaces. Flushing could presumably have occurred at any period later than the Middle Miocene. The head values in the Mesozoic sandstones in the northern Sirte Basin must be evaluated with caution. The ion concentration is frequently in excess of 100,000 ppm and the head change in converting to a fresh water equivalent is then very large; the effects of compaction in these deeper levels could also be misleading. The trends in the formations at a more shallow level to the south of latitude 27°00'N which contain moderately fresh water can perhaps be considered reasonably valid.

5.2 Regional Flow Patterns in the Post-Eocene of the Sirte Basin

Various factors need to be takento account in considering the piezometric surfaces map of the Post-Eocene. Piezometric head measurements are from wells drilled and completed in the upper levels of the sequence, generally between 200 and 300 feet below the water table. In consequence of the dip of the Miocene and Oligocene upper boundaries, measurements relate mostly to the PMM from a short distance east of the outcrop boundary and to the west of this general line to either the Miocene or Oligocene according to location (Figure 10).

The general direction of flow in the upper levels of the Post-Eocene is between northeast and north, directed towards the groundwater discharge areas (sabkhats) which occur in the vicinity of the Gulf of Sirte and in the low-lying area between the Gulf and the Quattara - Siwa Depressions. Other discharge areas of less significance are the oases of Augila, Marada and Tazerbo.

In the southern Sirte Basin, there appears to be no significant piezometric head differential between the PMM and the upper LMM. The feature accords with the lithological relations which indicate probable hydraulical continuity. Farther north within the Central Phase 1, a marked differential does occur and is shown in Figure 22. The feature is probably the result of the combined effect of transmissibility differences and discharge differentials between the two subdivisions. A fuller discussion of these relations is presented in the Final Report on the Phase 1 Area (Wright et al, 1974). From consideration of the north-south cross-sections in Figure 10, it would seem that discharge is likely to be restricted with consequential head buildups (and development of saline water) in the Oligocene and deeper Miocene, particularly in the north-east corner of the Sirte Basin. Somewhat surprisingly perhaps, there is no marked head differential existing throughout the Post-Eocene succession at T(Q1-65) at the north-west corner of the Phase 2.

Deductions from the flow patterns and gradients in terms of the hydraulic characteristics of the Upper Post-Eocene need first to account for the likelihood or otherwise of recharge over the outcrop areas. Present day climatic considerations, the apparent moisture deficiencies in the surface sands and the general

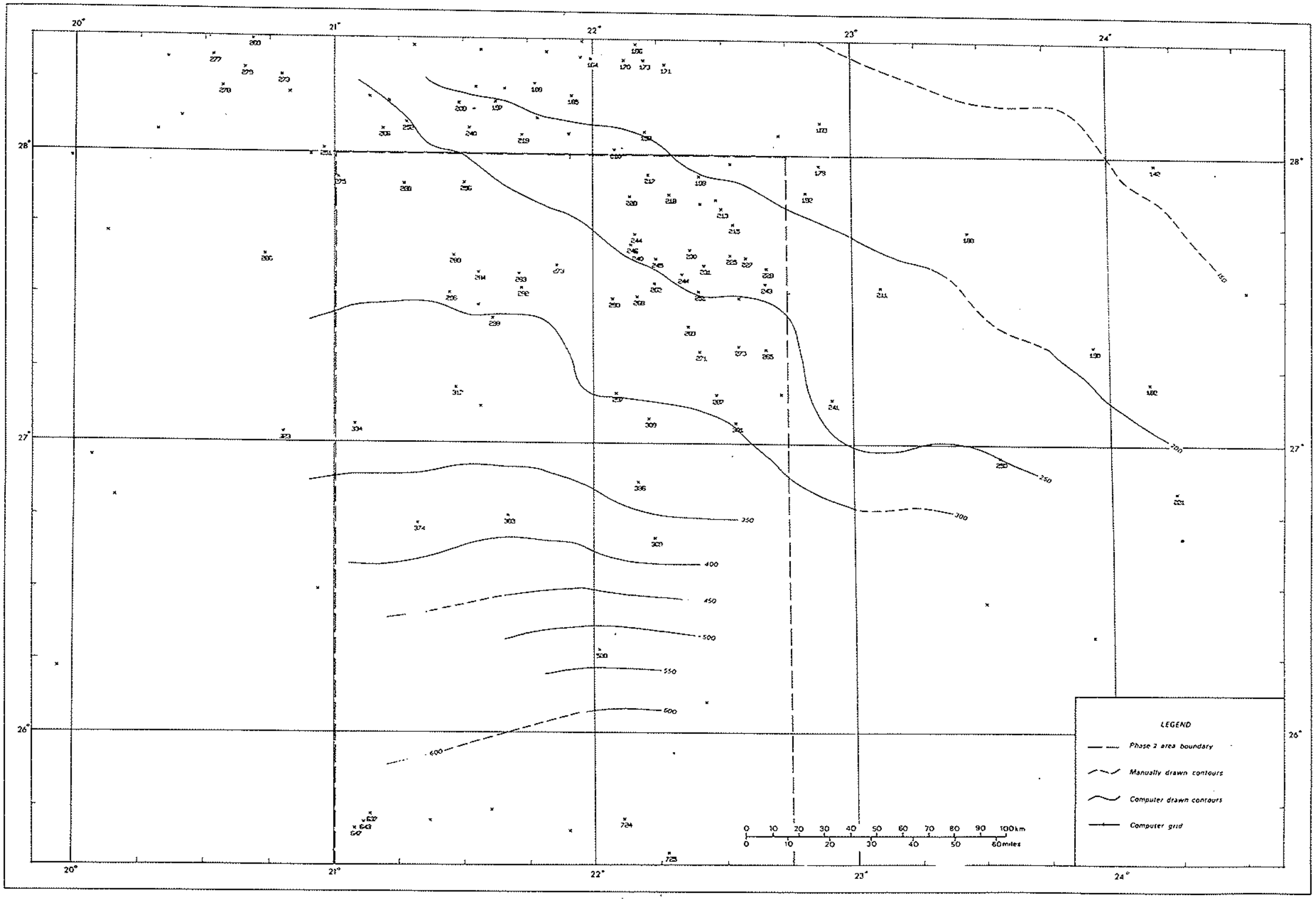


Figure 23. Piezometric surface map in Upper Post-Eocene (computer plot).

lack of run off evidence viewed in relation to the low rainfall, all indicate the unlikelihood of current recharge. So also do the general trend of the piezometric contours which appear quite independent of topographic relief. An exception to this relation is apparent in the bending of the contours on the extreme western margins of the Basin which could be the effect of recharge and the feature accords perhaps with the evidence of local surface run off from the Haruj Al Aswad to the west. It should be noted that these effects need not relate necessarily to current recharge but to a sufficiently recent event that the transient effects have not been dispersed. It is known for example that elongated zones of fresher and younger (6000-8000 years) water occur within the Upper Post-Eocene against a background age in the main aquifer of 30-40 000 years. The absence of any head build-up over such zones must indicate that sufficient time has elapsed for hydraulic equilibrium to be re-established within the aquifer.

Current recharge into the Post-Eocene system from outside the main basin in the far southern embayment of the Tibesti Sarir is possible and head levels in the south-west would be affected. It must be remembered that the Post-Eocene is extremely attenuated in this area, being reduced mainly to a thin surface cover overlying shallow Basement and Palaeozoic rocks. Of greater significance is the probability of hydraulic continuity between the Post-Eocene and the Nubian to the south of Tazerbo below latitude 26°00N. The comparative head levels suggest this as well as the generally sandy lithology of the reduced Tertiary sequence (cf. log of D1-71). Farther north a significant head differential between the Post-Eocene and the Nubian occurs with the consequent possibility of a state of upward leakage which would have an effect on head values and also incidentally onwater quality. Since the Eocene and Palaeocene increase rapidly in thickness northwards and include tight limestones, clays and evaporites, the likelihood of extensive upward leakage in the Phase 2 Area to be north of 26°00N does not seem to be great. Leakage along fault zones is a possibility and may account for the anomalous water quality in some of the southerly locations such as F1-65.

These various considerations suggest that the general form of the piezometric surfaces in the Upper Post-Eocene is probably a transient or semi semi-steady state condition* related to discharge in the north and in the south by ancestral head levels and significantly in the south-centre by interaction with the Nubian of the Kufra Basin. The northward 'bulge' in the contours in the southern Phase 2 may be related to this interaction; the south-easterly trend of the contours in the area east of Phase 2 may show the effect of the downward gradients along the Palaeozoic outcrop away from the controlling Nubian levels in the centre. To the west, the contours would relate also to flow within the attenuated Post-Eocene into the Tibesti-Sarir embayment and to possible recharge, either current or recent, from the Haruj Al Aswad.

These conclusions are significant in that the piezometric surface map can in general be related to the transmissibilities of various cross-sections of the Upper Post-Eocene assuming no water loss or gain within the system. Leakage from the Nubian in the far south must be accounted a possibility but vertical components within the Post-Eocene itself do not appear significant within the Phase 2 Area limits. Most of the dual piezometers drilled in the present programme indicate a small upward gradient between the deeper LMM (Zone 'c') and the PMM aquifer. Flow is therefore sub-horizontal at least down to Zone 'c', and this upper section above the main clay of zone 'd' can perhaps be regarded as hydraulically continuous (see section B-B Figure 14*). The gradient is steeper in the south (1:1000), decreasing northwards to approximately 1:3000, and indicating a northward increase in transmissibility within the 'unit'. The feature correlates with the results of the few aquifer analyses at test sites carried out to date. The higher transmissibility in the north appears mainly the result of the upper aquifer occurring progressively more within the more highly permeable unconsolidated sands of the PMM as compared with the finer grained less permeable sands and sandstones of the upper LMM. In the far south, the aquifer occurs wholly within the LMM or deeper horizons which would account for the steeper gradients. The effects of possible upward leakage are rather difficult to assess unless a general area of leakage is also postulated, but the effect will be to exaggerate the transmissibility up-gradient and within the zone of leakage. The conclusions are also significant in that allowing for possible leakage in the south, the gradients and flow directions can be utilised in the calibration of a steady state model.

* semi-steady state applies to a non-recharging aquifer when the cone of depression from discharge areas reach the limiting boundaries; head levels then continue to fall in parallel fashion so that dh/dt is independent of position.

5.3 Hydrogeochemistry

During the IGS investigations in 1967 and 1968, the majority of water wells existing at the time in south-central Cyrenaica which includes the Phase 2 Area were conductivity logged and sampled.

TABLE 7

CHEMICAL ANALYSES OF WATER SAMPLES FROM THE PHASE 2 AREA

I.G.S. Reference Number	Locality and water well position when available	Ground elevation (metres) amsl	Sample type	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}	Sr^{2+}	HCO_3^{-} Lab
74/119	R1-80 E		n.s.[1]	29	26	339	45	60.8	556	2.1	
/120	U1-80 SE	90	n.s.	11	17	216	45	38.2	349	0.20	
/121	F1-105		n.s.	192	102	543	25	372	1026	5.2	
/122	X1-80 N	95	n.s.	106	107	684	45	3.4	1450	3.3	
/123	C1-105	81	n.s.	4.3	3.0	173	16	22.5	132	0.06	
/124	V1-80	107	n.s.	17	23	192	14	47	256	0.85	
/125	Z1-80	92	n.s.	35	35	289	16	32	488	0.50	
/126	L1-71 SE		n.s.	1.6	1.4	261	18	22	282	0.06	
/127	L1-71 SE		n.s.	2.0	1.4	265	24	22.5	283	0.05	
/128	F1-59		n.s.	5.4	3.6	248	23	47	337	0.13	
/129	Z1-65	139.	n.s.	12	18	204	20	134	199	0.26	
/130	B1-65	156	n.s.	34	20	286	22	33	545	1.6	
/131	KK1-65 E	105	n.s.	51	41	222	33	174	332	1.6	
/132	JJ1-65	99	n.s.	30	53	311	42	31.4	653	0.71	
/133	T1-71 S	177	n.s.	3.8	10	502	22	107	474	0.17	
/134	B1-135 S	154	n.s.	69	53	381	35	146	760	1.9	
/135	G1-65 N	163	n.s.	89	94	464	46	32	1193	2.0	
/136	A1-135 SW	123	n.s.	7.2	31	211	34	20.6	365	0.05	
/138	DD1-71 SE		n.s.	148	83	388	23	17	1076	3.6	
/139	T1-71 N	177	n.s.	51	32	250	14	21	509	1.8	
/140	AIN GEZIRI		n.s.	260	110	750	220	1337	2060	3.7	
/141	AIN GIULAT	196	n.s.	66	40	165	59	171	1645	0.64	
/142	T1-80	131	n.s.	32	55	375	24	171	684	1.1	
/143	AA1-80	124	n.s.	7	2.5	700	28	151	778	0.12	
/144	F1-65	208	n.s.	125	110	675	109	135	1790	1.9	79
/148	Q1-65 S	162.	p.s.[2]	131	71	308	19	465	449	4.1	199
/149	T(Q1-65) A 2[3]	162	p.s.	84	58	258	28	466	345	2.8	
/150	T(Q1-65) A 3	162	p.s.	149	85	313	35	588	423	4.5	
/151	T(Q1-65) A 5	162	p.s.	120	71	251	29	466	343	3.7	
/152	T(Q1-65) A 7	162	p.s.	107	63	251	17	368	350	3.1	
/153	T(Q1-65) A 1	162	p.s.	118	70	258	21	451	350	3.3	211
/154	T(Q1-65) A 4	162	p.s.	147	87	276	31	569	382	4.1	
/155	T(Q1-65) A 6	162	p.s.	118	71	315	21	433	346	3.3	
/158	Sarir Field 537		p.s.	58	30	154	20	54	270	1.7	
/159	Sarir Field 540		p.s.	71	36	176	20	48.5	333	1.9	
/160	Sarir Field 542		p.s.	52	30	145	20	47	246		
/161	Oxy Road Well 1	223	n.s.	6.5	11	238	81	60		0.15	
/162	Kufra-Way	225	n.s.	37	28	258	105	185		0.76	
/163	Maabas-Yousef	199	n.s.	39	17	30	18	41		0.29	
/164	El-Wadi-Farm		n.s.	98	48	308	35	246		1.1	
/165	Ain Gezira	198	n.s.	58	35	220	47	149		0.60	
/166	F1-65	208	n.s.	128	23	815	97	80.4		1.9	

(1) n.s. - near surface within casing or well (2) p.s. - pumped sample (3) Numbers refer to screen interval (see Appendix 4)

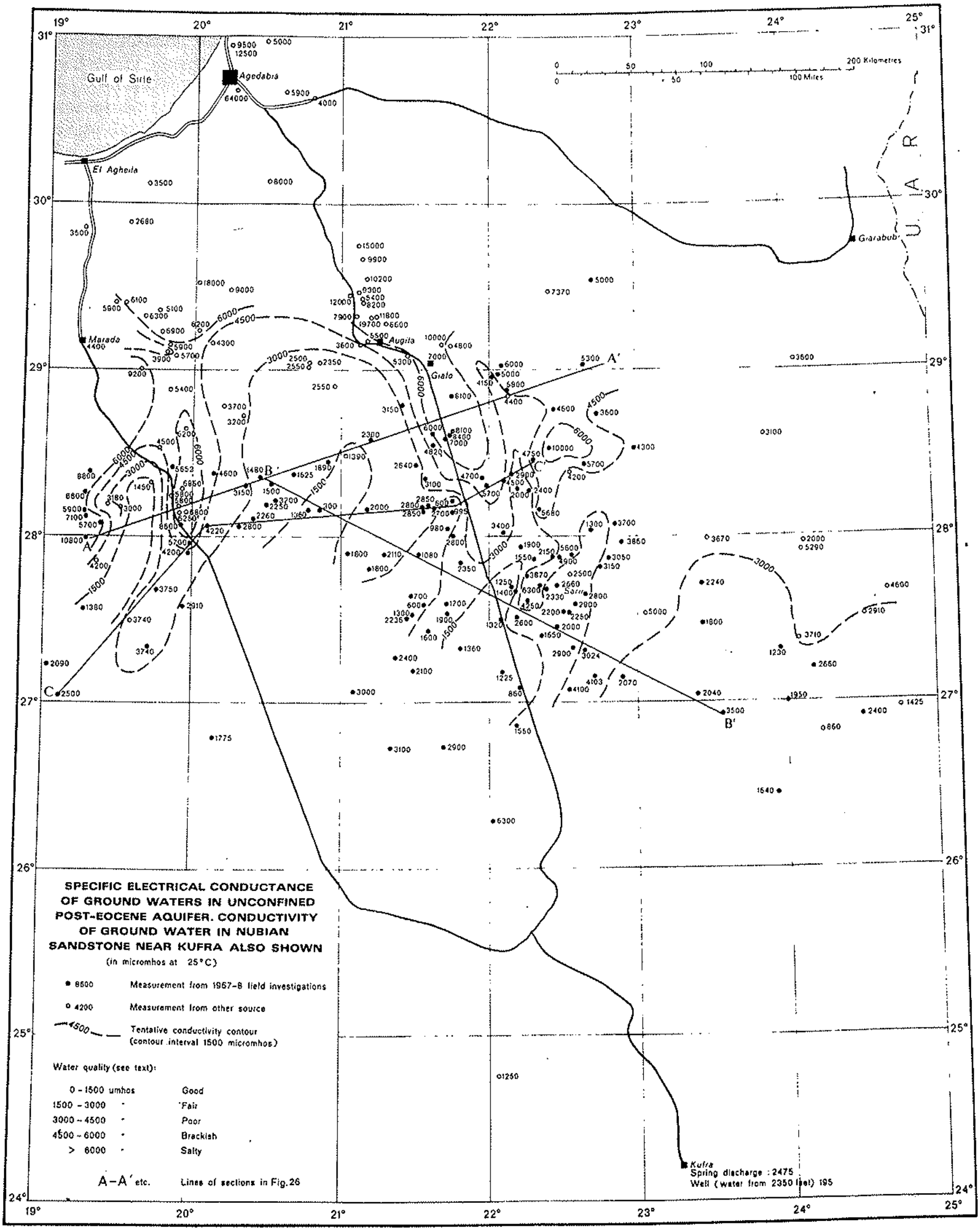


Figure 24. Specific electrical conductance of groundwaters in unconfined Post-Eocene Aquifer. Conductivity of groundwater in Nubian Sandstone near Kufra also shown.

Water samples were collected within the well casing and possible changes which may occur to standing water within the casing are discussed in the Final Report of the Phase 1 Area. It was noticed that in many cases, the measured conductance remained constant throughout the casing into the perforated section, indicating that any changes which may have occured since pumping ceased are unlikely to be very significant. Mineral analyses of many of the samples collected have been made including measurements of major and several minor elements. The analyses are listed in the Report prepared for British Petroleum Co. (Libya) Ltd. (Wright and Edmunds, 1969).

During the current investigations additional water samples were collected and analytical results are shown in Table 7 and in the Appendices to this Report. The samples were obtained from the following sources:-

1) Water wells drilled for oil company use in the period subsequent to May 1968.

2) Wells drilled as part of the test drilling programme for the current investigations. The majority of these are of moderate depth, generally less than 700 feet bgl, since they are concerned with evaluation studies for the upper levels of the Post-Eocene aquifer. The one exception is T(Q1-65) which has been drilled to the base of the Oligocene and sampled for water content at varying intervals in between.

No re-evaluation of the detailed hydrogeochemistry is included in this Report and reference can be made a fairly full discussion in the IGS Report to B.P. Petroleum Company of Libya (Ltd) - Wright and Edmunds, 1969. The aspect to which main consideration is given in this Report are the general quality changes with particular reference to areas and levels of immediate significance in relation to current planned development.

5.3.1 Water Quality Changes

Quality changes are considered here in terms of specific electrical conductance since this is a parameter which can be readily measured either on samples or within the formation using a downhole logging tool. The probe utilised in the 1967-8 investigations was a fairly coarse megger device which measured conductivity uncorrected for temperature or capacitance effects. The probe utilised in the recent investigations was more sophisticated and capable of measuring both conductivity and temperature corrected for capacitance effects. It has been customary to log a hole to total depth and to obtain at least one check depth sample.

The majority of the water wells drilled in the Phase 2 Area were designed to supply water for the deep oil exploration drilling. Usually three water supply wells occur at any one site, commonly drilled to between 200 and 300 feet below the water table, cased with 6 5/8" casing and screened with a single joint (33 feet approximately) of torch-slotted casing near the base. The three wells are generally of the same total depth but in a few cases, presumably if the first well in a group produces badly, wells drilled to varying depths may have been completed. In such cases, screens may be set at two or more intervals, e.g. wells associated with P1-65.

Due to the coarse slotting, many wells have sanded-in since completion. Corrosion of the casing may also occur, notably where the ground water has a high dissolved solids content, and sand entrance may then occur at levels other than the screening. Oil company records very rarely distinguish locations of the individual wells in a group nor are numbers commonly marked on the well head. In consequence, unless the plumbed depth is distinctive, it is not generally possible to distinguish individual wells within a group at a single site. The matter is not critical where perforated intervals are coincident but may be so where depths do vary and quality changes are apparent in different wells. Conductance logs will sometimes provide information on varying levels of perforation.

Quality changes do occur both laterally and horizontally within the Post-Eocene aquifer system. These changes must be considered in relation to the aquifer lithology and significant stratigraphic levels. The majority of wells drilled to the north and east of the PMM outcrop boundary are completed within the PMM (Calanscio) Formation. To west and south of the outcrop boundary, wells in the Phase 2 Area are mostly completed within Zone 'a' of the LMM. Some wells close to the boundary may be screened in both the lower PMM and upper zone 'a' of the LMM. The PMM is commonly more permeable than the LMM but both formations are here essentially hydraulically continuous.

The initial observation well at T(T2-65) was drilled to the base of Zone 'c' of the LMM and the second test production well completed at this site was screened in the LMM Zones 'a' and 'c'. Hydraulic head within the deeper LMM proved to be slightly higher than the upper LMM/PMM and water quality showed minor differences which will be described. Many of the future production wells in this area will have a similar completion.

Information on the water quality in the deeper LMM and Oligocene can be obtained mainly from the geophysical logs which provide a fairly

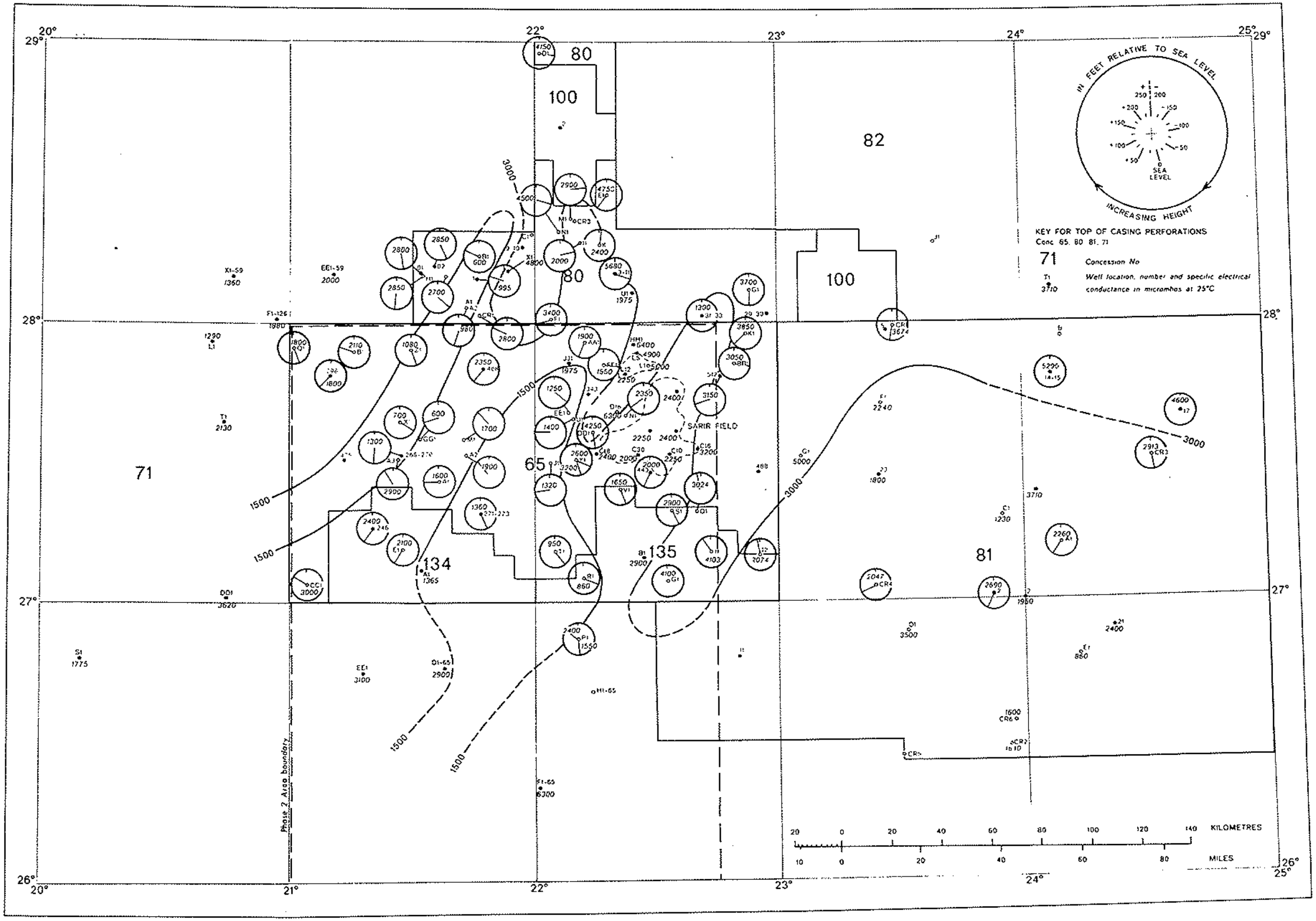


Figure 25. Specific electrical conductance of groundwater in Upper Post-Eocene Aquifer, Phase 2 Area.

SPECIFIC ELECTRICAL CONDUCTANCE OF FORMATION WATERS IN WELLS IN CONCESSIONS 65 AND 134/5

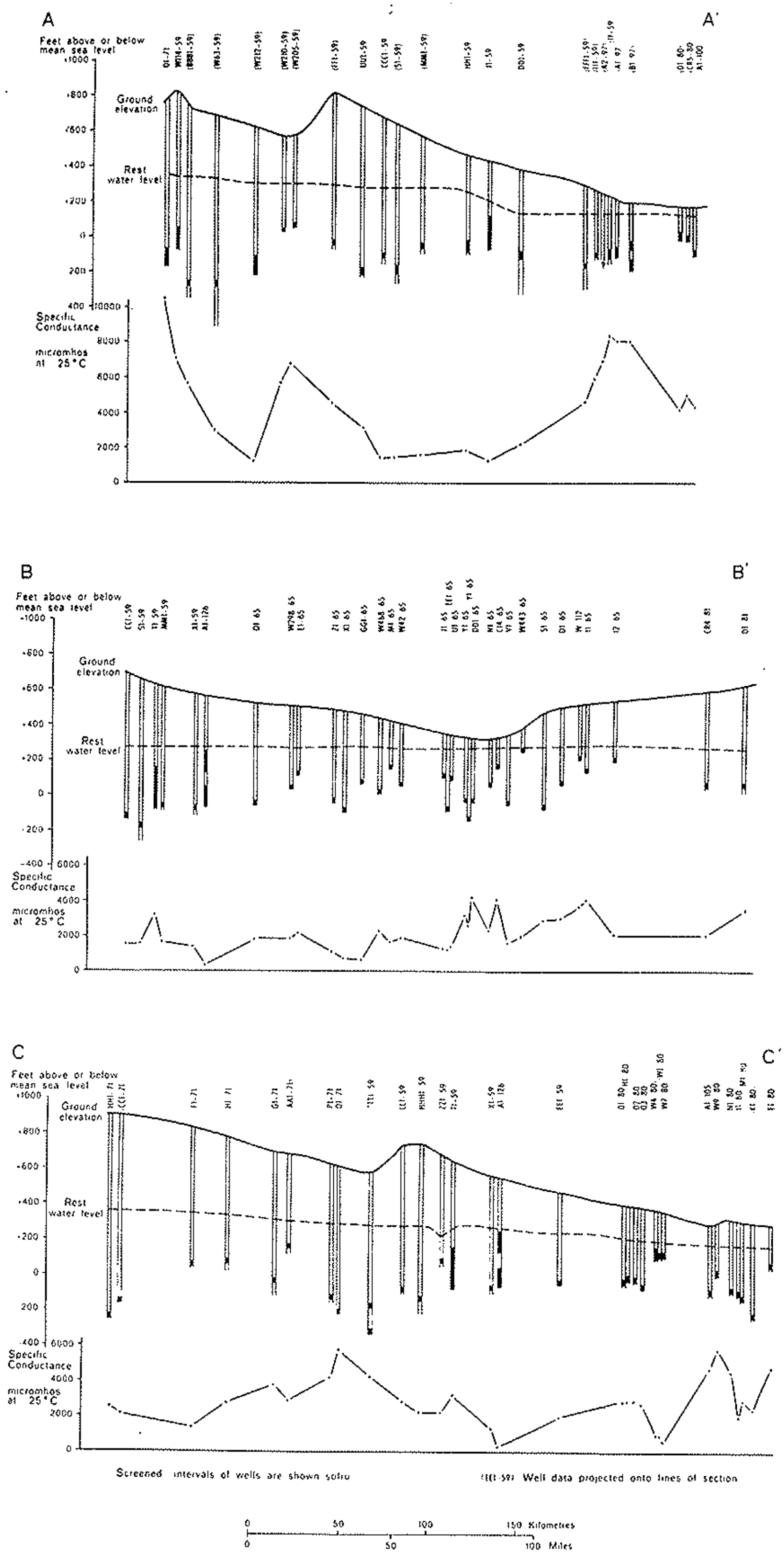
1	2	3	4	5	6
A1 -65	2- 6	485	390-400	118/128	1600
A2	15- 17	456	401	195/206	1900
A3	131-133	508	298-341	203/223	2900
B1	8- 10	512	380-400	152	2110
C1	12-14	386	314-365	95/114	2100
C3	23-25	372	319	93	2680/1820
C9	58- 59	352	340-345	46	2100
C10	45- 47	408	309	160	2250
C15	76- 77	373	283	138	1900
C18	84- 85	364	284-470	?	2400
C22	101-103	326	222-242	98/144	2400
C23	119-121	332	271-285	87/107	4050
C24	353A	332	341	36	3400
C25	157-159	348	280-281	111/137	3700
C27	161-162	353	257-281	113/140	1175
C28	174-175	345	299-316	82/ 99	1700
C29	145-147	385	282-306	128/151	2000
C30	113-115	350	318-329	69/ 81	2000
C31	185-187	336	231-253	117/146	3900
C32	230-232	415	590-600	?	200
C35	259-261	474	561-592	-32/-84	2400
C37	240-242	343	436-466	-47/-79	2660
C39	274-276	378	530-546	-122	2600
C40	292-294	328	448-455	- 75	1100
C41	306-308	402	459-462	- 13	2250
C42	224-226	348	357-404	-22/-36	2400
C43	303-305	354	405-407	- 9	1400
C44	209-211	330	282-294	79	3500
C45	218-220	340	280-285	94	1440
C46	204-205	344	304-310	77	2100
C47	139-141	333	302-308	74	3200
C48	197-199	340	252-270	112	1350
C50	188-189	354	280-283	117	2900
C51	227-228	435	500-602	-15/-107	2750
C54	172-173	378	303	121	1750
C55	333-335	435	397-475	6/ 55	2250
C56	194-196	339	271-274	105	2100
C59	237-239	341	420-444	-31	1200
C60	362-364	331	324-361	10/ 51	2500

COLUMNS:

1. Oil exploration well site number according to Company code.
2. Water well numbers from Company records (consecutive between range).
3. Average ground elevation in feet above mean sea level.
4. Depth range in feet below ground level of water wells at site.
5. Upper levels of perforated intervals in feet ± msl. (if range small, one value only may be quoted). Data have been taken mainly from summaries in Company files and some errors noted. Reference may be necessary to original well completion forms.
6. Specific electrical conductance in micromhos at 25°C. Values determined by borehole logging to perforated intervals where possible and corrected by sample checks.

1	2	3	4	5	6
C61	340-342	373	337-359	70	2250
C63	176-178	336	222-224	152	5300
C67	379-381	357	203-326	70/134	1500
C68	385-387	352	398-438	-17/-43	1120
C69	366-368	433	326-423	51/152	2950
C70	136-138	349	292-300	97	1600
C71	391-393	353	347-353	48	1750
C73	337-339	406	416-438	12	2400

C74	382-384	352	283-286	109	3200
C75	373-375	348	335-386	53/-3	2600
C76	388-390	351	324-336	62	2350
C77	397-399	440	367-465	16/118	2800
C78	314-316	348	400-416	-16	1850
C79	406-408	353	358-361	36	1100
C80	410-412	341	350-371	33	1550
C81	423-424	384	358-368	66	2600
C82	428-430	402	428-497	12/ 79	2600
C83	419-421	387	400-410	20	2500
C89	450-452	344	441-447	-48	3100
C90	456-458	485	501-579	2/-50	2350
C91	472-474	425	488-495	-31	2200
-	222-223	321	352-371	51/-10	3600
-	311-313	348	395-400	-3	860
-	330-332	339	376-407	4	2250
-	394-396	366	447-460	-36	2900
-	425-427	414	437-463	26/-8	2000
-	469-471	411	495-499	-43	2550
-	479-481	433	523-525	-51	2825
D1	21- 22	576	305-320	312/323	2800
E1	321-323	527	514-524	48/ 61	2100
F1	28- 29	672	305	412/423	
G1	206-208	529	580-649	-20/-87	4100
H1	32- 33	589	312-344	299/332	5300/6400
I1	56- 57	523	348-405	192/221	4103
I2	74- 75	677	500-538	199/235	2074
J1	92- 94	380	300-385	60/124	1320
K1	86- 89	?	325-546	68/143	3850
L2	437-439	333	407-471	-26/-98	5600
L3	444-446	311	402-409	-58	3700
L4	453-455	315	401-435	-40/-77	4400
L5	476-478	302	378-408	-33/-44	4900
L6	462-464	321	343-481	19/-119	2750
L7	482-484	320	404-412	-50	5750
L8	497-499	316	404-409	-44	5100
L9	485-487	308	388-392	-40	4600
L10	509-511	307	400-430	-55	4900
L11	503-505	311	412-438	-62	3250
L12	506-508	327	391-428	-24/-58	2250
L13	515-516	314	404-603	-17/-234	2300
L14	520-522	326	433-488	-67/-122	2150
L15	523-525	304	404-421	-59	3500
M1	134-135	453	298-307	194/203	1700
N1	122-124	331	280-285	84/ 94	2350
O1	152-153	508	417-450	104/159	3024
P1	233-235	533	615-731	5/161	1550/2400
R1	247-249	459	544-601	-31/-114	950/1020
S1	250-252	490	550-601	- 5/-67	2900
T1	262-264	424	504-517	-33/-42	950
V1	283-285	367	424-453	-10/-41	1650
X1	253-255	482	571-581	-48/-54	700
Y1	265-267	358	391-501	12/-57	2600/3200
Z1	295-297	458	501-515	- 4/-15	1080
AA1	167-169	312	258-308	48/100	1900
BB1	300-302	472	595-602	-77/-97	3050
CC1	327-329	611	468-470	183/185	3000
DD1	459-461	340	376-393	2/-9	4250/2820
EE1	494-496	355	442-450	-23/-50	1250
GG1	517-519	484	417-425	100/108	1600
HH1					6400
HH2					8000
HH3					8700
GG1	592-593	326	385-387	-57	2620
KK1	598-599	345	381-405	34/55	1750
LL1					1960
A1-134					1280/1450
A1-135					2900
C1-135					3900



After Wright and Edmunds, 1969

Figure 26. Schematic sections indicating relationship between chemical quality of the water and depth to screened intervals. (Lines of section shown in Figure 24).

coarse resolution and from the one sampled hole drilled to date at T(Q1-65) - Appendix 4.

Figure 24 shows the general variations in specific electrical conductance in the upper levels of the Post-Eocene in Central Cyrenaica based on data collected in the 1967/68 investigations. Figure 25 is a more detailed map of the Phase 2 and marginal areas incorporating the later data from the current investigations and also diagramatically showing the upper level of perforations of many of the wells. The level is an average value where a range is apparent in the wells at a single site and individual wells cannot be distinguished. Fuller details are tabulated in Table 8 . Within the general intervals screened, it is apparent that changes in conductance in a vertical plane are generally of a much lower order than changes in a horizontal plane. The map therefore represents significant changes occurring laterally within the upper levels of the Post-Eocene (mainly PMM, subordinate LMM, Zone 'a') in south central Cyrenaica. This is apparent in the cross-sections Figure 26, also reporoduced from the 1969 Report (op. cit).

The observed lateral changes in water quality do not appear to have a close lithological control. The poor quality of water in the north-central Phase 2 area may possibly be related to rather more significant proportions of sandy carbonates in the PMM sequence (see geological logs for DD1, HH1, L1-65 etc) but the correlation is by no means certain. An alternative possibility which is considered more likely is that these belts of varying water quality may relate to different recharge periods and thus vary in age. On the assumption of relatively homogeneous lithology, older water will in general be more highly mineralised. Confirmatory evidence for this type of occurrence was found in the Phase 1 Area in which a continuation of the belt of low mineralised water extending in western Phase 2 (X1-65 etc) has been dated 9300 years occurring within a background value in adjacent more highly mineralised water of 25-30 000 years. Sufficient numbers of radiocarbon analyses were carried out to support strongly the validity of the dating.

Information on the water quality to the south of 27°00'N is limited by the few wells occurring. Mineralisation is generally higher than in wells of similar depth farther to the north and one, at F1-65, shows a specific conductance of 5300 micromhos. Most of the wells (F1, D1-65, EE1-71) are screened within the LMM and the increase in mineralisation might possibly be correlated with this formations' lithology. The specific conductance of the water at F1-65 does seem anomalously high and the possibility of leakage from the Mesozoic sandstone aquifer (Nubian) at depth must be considered since a head differential exists. The presence of a thick series of tight carbonates, evaporites and shales within the Lower Tertiary is considered to indicate the improbability of large scale leakage and movement along structural planes might be marginally more likely. Analyses of water from the deeper aquifer (chemical data from B. P. Company records) and the mineralised sample from F1-65 have been plotted on a Piper diagram (Figure 27) and the contiguity of the plots support the possibility. Consideration of the minor elements would probably be more definitive but unfortunately none have been analysed.

The oil companies' water wells are, for practical reasons, screened at appreciable depths below the water table and the variations in quality observed are considered to be generally representative of the upper levels of the Post-Eocene aquifer. In the current series of investigations, observation wells screened close to the water table have been completed and results of conductance measurements have shown that in this fairly localised area in the central well field that mineralisation near the water table is generally higher (conductance 2400/5400) than at depth (1010/2400). Details of the values and appropriate screen and water levels are given in Table 9. Available evidence suggests that this poorer quality water might persist to depths of 100/150 feet below the water table and provided that the lithological variations can be allowed for, correlation of the electric logs with the known formation water resistivity might permit sufficiently precise extrapolation. An example illustrating the variations which can occur in a series of wells screened at varying levels is shown in Figure 28. It is assumed that the conductivity of the water opposite the screen will be representative of the water in the aquifer at that level and that in the casing of the discharge during pumping which could be derived in part from higher or lower levels. The short string of 02 which is screened at 128 feet below the water table (Figure 5, Appendix 3) shows the highest conductance. The conductance in the casing is lower and similar to that derived from the deeper horizons which rather suggests that the intervening clay below the short string screen is not an effective barrier. The feature is also indicated by the pumping test results.

No significant change occurs across the screened interval in the long string of 02 and the difference between the conductance values in 02 and W. W. Central which is screened in the LMM Zone 'a' suggests a chemical discontinuity at least across the boundary of the PMM-LMM. The screen of Water Well Central and the upper screen of 01 are at the same level and conductances are comparable. However an increase occurs in 01 opposite the second screen and indicates a

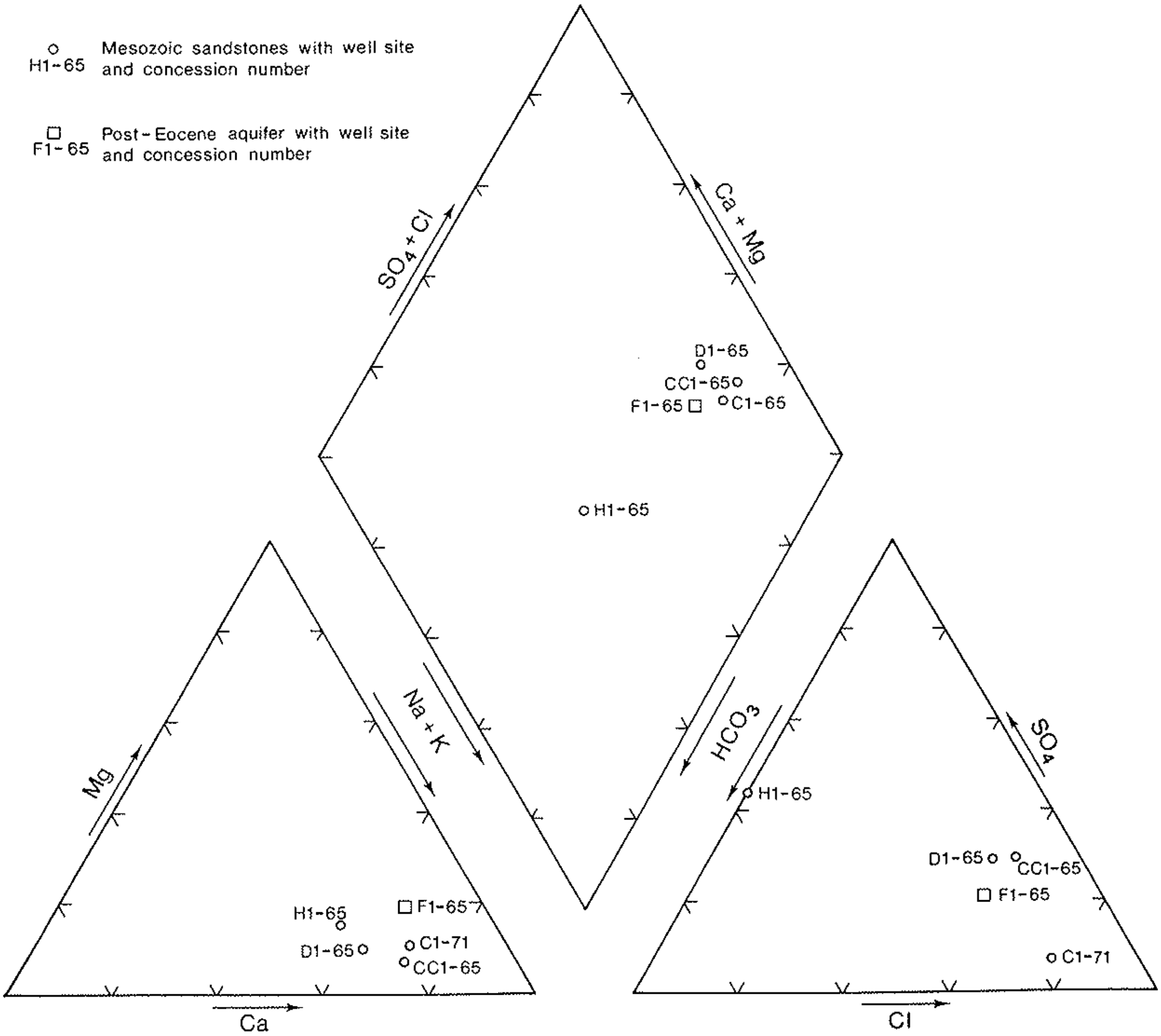


Figure 27. Trilinear plot of groundwater analyses from Mesozoic sandstones and Post-Eocene aquifer, Sirte Basin.

TABLE 9

Specific electrical conductance of formation water (pumped discharge) in micromhos at 25° C and static water level in casing in feet below common well datum in dual observation piezometers in Sarir Well Field.

1	2	3	4
A 100 W/01			
s.s.	350-380	3450	201.5
l.s.	?	2400	200
A 100 W/02			
s.s.	240-270	5400	200.1
l.s.	527-760	2000	199.8
A-130 E/01			
s.s.	270-301	2400	167.44
l.s.	505-765	1870	167.1
A-130 E/02			
s.s.	328-360	2360	167.68
l.s.	506-775	-	-
C-132 E/01			
s.s.	314-345	3180	158.1
l.s.	496-718	1010	157.5

COLUMNS:

1. Well site number according to convention by Kufra and Sarir Authority.
   s.s. = short string; l.s. = long string
2. Perforated interval in feet below well datum (usually ground level)
3. Specific electrical conductance in micromhos at 25°C
4. Static water level in feet below well datum.

TABLE 10

Specific electrical conductance of formation water, in Post-Eocene at test drilling sites, Phase 2 Area (Pumped samples)

T(U1-65) : Ground elevation = 350 ft amsl

1	2	3	4
CW 154	217-260		
" 155	226-266		
" 156	226-270		
T(U1-65) 01A	(160-176) (570-580)(i)		
T(U1-65) 01ss	(311-319) (411-420)		
T(U1-65) P	256-504	1360-1450(iii)	

T(FF1-65) : Ground elevation = 308 ft amsl

1	2	3	4
CW 489	378-424		
" 490	486-430		
" 493	388-431		
T(FF1-65) 01	(285-295) (510-519)(i)		
T(FF1-65) 02	(370-379) (425-434)		
T(FF1-65) P	356-557	1890-1970(iii)	

T(T2-65) : Ground elevation = 414 ft amsl

CW	528	416-453	2350	
"	529	411-453	1360	
"	530	411-454	1320	
T(T2-65)	01	(419-444) (468-493) (i) (716-731) (800-817) (ii)	3400	
T(T2-65) 02ss		243-257		
T(T2-65) 021s		(295-311) (355-371) (i)		
T(T2-65) P		299-557		
T(T2-65) FGW		324-825	1710-1740	

T(P1-65) : Ground elevation = 533 ft amsl

CW	233	(528-549) (614-636) (638-731)	1540	NW
"	234	(365-400) (689-734)	2240	Centre
"	235	(327-417) (570-015)	1550	SE

T(Q1-65) : Ground elevation = 532 ft amsl

T(Q1-65)	946-976	2100
"	1094-1124	2160
"	1312-1342	2200
"	1461-1491	2450
"	1680-1710	2700
"	2011-2041	no production
"	2270-2300	no production

NOTES:

(i) LMM Zone 'a'

(ii) LMM Zone 'b'

(iii) Pumped sample (range during aquifer test)

COLUMNS:

1 Water Well number from Company Records (CW = Company Well)

2 Perforations in feet bgl (FG = Fibre glass screened well)

3 Specific electrical conductance in micromhos at 25°C

4 Well site location (in most cases refer to appropriate appendix)

discontinuity of sorts across an intermediate clay layer in the LMM Zone 'a'. The deeper screen of 01 shows a further increase still. The casing conductance is most closely related to the top screen. During the pumping test of the F. G.* well which is screened entirely within the LMM, the discharge conductance varied between 1740-1710 micromhos, intermediate between the extremes shown.

A further anomaly exists in the values from the three existing wells (Table 10). All wells are supposedly screened at the same levels but whereas two have the same conductance, the third is appreciably higher. The feature may relate to inaccurate well records; alternatively, it could result from damaged or corroded casing giving access to a zone of more highly mineralised water.

The general evidence of the available data points to an increase in mineralisation in the highest levels of the Post-Eocene aquifer close to the water table. How extensive this feature is in the Phase 2 and marginal areas is uncertain and some indication might be obtained by log analysis. Understanding the cause for the increase might also provide pointers and one possibility is that the increased mineralisation may relate to concentration by evapotranspiration effects developed at a time when the water table stood close to the ground surface. If this is so, the likelihood is that the feature may be largely restricted to the vicinity of the topographic low.

The overall results may be summarised as follows. Within the Phase 2 Area north of latitude 27°00N, significant lateral variations in quality occur and the numbers of sample points strengthens the likelihood of the validity of the contours. These variations appear largely unrelated to any obvious lithological changes and a possible explanation correlates quality with varying recharge periods. Superimposed on these changes, an increase of mineralisation in the highest levels close to the water table is evident in the area drilled to date for production wells. More detailed log analysis might give indications of the extent of the feature. The increase in mineralisation may be due to ancestral evapotranspiration effects and as such may be localised in the topographically lower-lying areas.

Changes in the deeper LMM and Oligocene in the northern Phase 2 cannot readily be predicted and factual information is mainly limited to the T(T2-65) data with that from associated production wells and from the samples collected at T(Q1-65). Spontaneous potential logs indicate fairly good quality over much of the Phase 2 Area. On lithological conditions, it might be observed that the LMM aquifer or certainly Zone 'c' and deeper levels are likely to be less related to the effects of recent recharge events and on that account mineralisation would be expected to correlate more closely with lithology.

To the south of latitude 27°00'N, in the southern Phase 1 Area, information is scanty. A quality zonation related to recharge events is possible and also near surface evapotranspiration effects in appropriate areas. A third possibility is upward leakage from the deeper Nubian. The various possible influences must be considered against the background of the near surface lithology of the LMM in order to predict general effects.

5.4 Aquifer Hydraulic Parameters

The required parameters are the transmissability and a storage factor which includes an artesian storage coefficient and the specific yield. These parameters have been determined in the Phase 2 Area by a combination of the following methods.

1. Analysis of pumping test data using a production and several observation wells.

2. Analysis of geophysical logs, mainly electrical (IES/SP), radioactive (gamma-ray and neutron) and sonic. Other than the gamma-ray logs by IGS, the logs available are those run in oil exploration wells, the majority by Schlumberger.

3. Analysis of grain size distribution data.

4. Regional patterns of piezometric contours.

Methods 1 to 3 provide data at localised sites whereas 4 provides more regional indications.

The programme of site drilling for aquifer testing includes an initial observation well (01) drilled to the maximum depth of interest and subsequently a second observation well and a production well. The production well is designed to give a high discharge of the order required for the proposed irrigation requirements, but the screen setting along with those of the two observation wells are designed to facilitate the carrying out of an aquifer test with recognised boundary conditions as outlined in section2 of this Report. Three sites have been drilled and pump tested to date*: T(U1-65), T(FF1-65) and T(T2-65) - see Figure 1. Two others have had an initial observation well drilled: T(P1-65) and T(H1-65). At T(H1-65), the results of the initial drilling proved unfavourable conditions (low permeability, high dissolved solids) and no production well is proposed. The five sites are located on a north-south line coinciding generally with the central axial

* F.G. Well is second test well at T2-65 which is completed with fibreglass casing and screen.

*October 1974

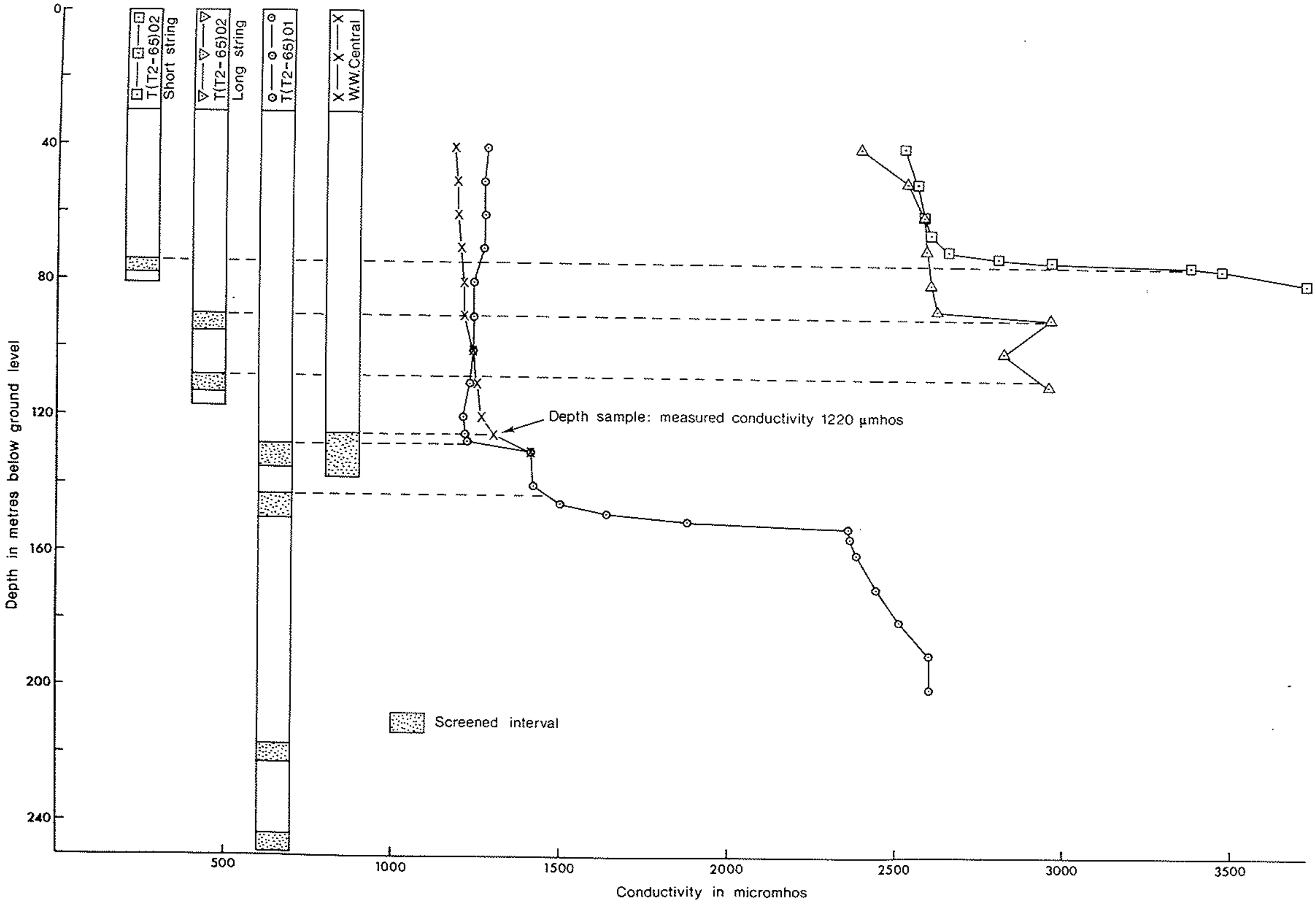


Figure 28. Measured conductance values in water wells at T(T2-05).

trough of the Sirte Basin and also with the zone in which soil and terrain conditions are best suited to irrigation.

Production wells within the depth interval of immediate interest occur mainly within the PMM and Zone 'a' of the LMM and to a lesser extent Zone 'c' of the LMM. The aquifer test programme has been designed to obtain the transmissibilities of defined intervals, called responding sections (RS) and extrapolation is required to determine the total transmissibility, in this instance to the base of Zone 'c' of the LMM.

The duration of the testing has been five days during which the response of all observation wells has been consistently artesian with a resulting value of the storage coefficient within the artesian range. Details of the testing and the site conditions are provided in separate Appendices for those sites completed and a summary of the results is included in the text of this Report.

5.4.1 Comment on Results of Aquifer Pumping Tests

Studies in the Phase 1 Area showed a fairly close correlation between permeability obtained through pump test analyses and that calculated by size analysis distribution (Wright et al, 1974). The correlation has been confirmed in the Phase 2 Area for unconsolidated formations within the responding sections at two of the sites tested. At FF1-65 average grain size permeability is 12.3 m/day as compared with the pump test figure of 10 m/day. At U1-65, the corresponding values are 4.8 and 4.5 m/day. Additionally, unconsolidated sections of the screened intervals with low grain size permeability have generally low log porosity (semi-quantitative consideration of neutron log) and show an equivalently low productivity on the flow velocity log. Thus there is a general accord between the various methods of evaluation, and provided good samples are available from unconsolidated formations in the Post-Eocene sequence, determination of the permeability can be made with a fair degree of confidence.

The permeability of cemented formations - calcareous sondstones to sandy carbonates, is more difficult to obtain. Recognition is based on sample observations and geophysical log data. Company lithological records in the Post-Eocene sequence are not detailed and only occasionally refer to the presence of such consolidated formations. A record is made of the presence of consolidated material in every 10 feet interval sampled during the current investigations but the relative proportions of unconsolidated to consolidated material are not necessarily easy to infer. Quite commonly, consolidated material may be limited to the top sieve and represent no more than a few per cent of the total sample. Sections with higher percentages of consolidated material usually show low porosity. Neutron logs in such sections tend to show rather variable 'peaky' responses and indications are that cementation tends to be weak and localised, possibly in thin bands.

Where cemented formations occur, along with unconsolidated formations in a screened interval, an order of relative permeability can be obtained from flow velocity data. The method would appear satisfactory if it can be assumed that well losses are a constant factor across a heterogeneous section. This seems unlikely but in the circumstances the method is the only one at present available. Consolidation is rarely sufficient to permit good coring and further efforts are recommended to improve the technique in these formations.

Information available to date has tended to indicate that cemented formations occur mainly in the rather finer grained Lower and Middle Miocene formations. Provisionally it has been assumed that the permeability will be dependent in part on the grain size variations with a reducing factor related to the cement. The true permeability will thus equal the grain size permeability multiplied by a correction factor 'C'. The usefulness of the correlation will depend on its validity and consistency. Clearly there are circumstances in which the permeability will relate to the grain size distribution such as in a banded sequence composed of both cemented and unconsolidated materials. The results to date in the few wells tested have indicated a correction factor of 0.5 which can be applied to the grain size permeability to determine true permeability. This has been determined in the responding intervals only but has been extrapolated to cemented formations outside this interval. Additional methods of obtaining or modifying a correction factor might include log analysis. The difference between log porosity and a porosity from grain size distribution would indicate proportions of cement. Cross-plots of a neutron and one other porosity cross-plot should indicate proportions of mineral components (quartz and carbonate) as well as provide a better porosity value. Detailed core analysis with thin sections will provide information on the distribution of the cement matrix and relation to the granular body of the rock. Whether these methods will prove sufficiently sensitive to provide good resolution in extrapolation of permeability remains to be seen. The values used in the present report must be regarded as very provisional.

Piezometric head data in the Phase 2 is mainly available from wells within the PMM and upper LMM formations although the little available evidence does show that the vertical differentials in the Post-Eocene sequence are of a minor order. Transmissibilities for the entire saturated sections down to the base of Zone 'c' of the LMM (the Middle Aquifer Unit) have been calculated at the five drilled sites, and the figures are listed in the Table below.

TABLE 11

Calculated Transmissibilities to the base of LMM, Zone 'c' at five drilled sites in the Phase 2 Area.

(values in m^2/day)

T(U1-65)	2340
T(FF1-65)	1447
T(T2-65)	1264
T(P1-65)	865
T(H1-65)	572

The calculation of the transmissibility of this section of the Post-Eocene is justified on the following counts. Production wells are designed not to exceed 1000 feet and in the location of the proposed well field in the central Phase 2, this will generally imply maximum depths to the base of Zone 'c'. To reach the next productive zone would require farther drilling through several hundred feet of clay. Additionally since the main clay layer in the LMM occurs below Zone 'c', the section above can be considered as an independent flow 'horizon' in which transmissibility should correlate with gradient.

The results of the site analyses show an increase in transmissibility northwards and this accords with the gradient of the piezometric surfaces map (Figures 22/23). The results may seem a little anomalous in view of the low specific capacities of the wells to the north but the controlling feature is the saturated thickness of the more permeable, largely unconsolidated formations of the PMM which increase in thickness to the north. The more practical aspects relating to well field development will be discussed in the next section.

The results of the site tests are summarised below and discussed in more detail for the sites completed in the Appendices. The results of the aquifer analyses at T(FF1-65) and T(U1-65) are regarded as satisfactory in view of the confirmation by grain size data. The computed low well efficiency is regarded as valid and indicating a need for further development. The values at T(T2-65) based on the pumping test analyses are regarded as exaggerated but no ready explanation can be provided. It is unfortunate that all the sites in the central and southern Phase 2 should have to rely largely on lithological sample data for analysis but it is hoped that some results from the initial test wells of the main production well programme will be available shortly.

5.4.2 Individual Site Summaries

5.4.2.1 Site T(U1-65): Figure 4 of Appendix 1

(i) Location: north-central Phase 2 Area

(ii) Static water level: 110 feet bgl

(iii) Stratigraphy and lithology

(a) PMM: 0-502 feet bgl; medium to fine sands and thin interbedded clays

1. Saturated thickness 392 feet
2. Sampled section: 100-500 feet bgl
3. Summarised sieve analysis data:

	Average	Range
(i) D50(microns)	642	285-1450
(ii) D40/D90	3.1	2.24-6.0
(iii) Kgs (USgpd/ft^2)	598	180-2200

(b) LMM Zone 'a': 502-633 feet bgl; fine to medium sands and calcareous sandstones and interbedded

1. Saturated thickness 131 feet
2. Sampled section: 500-630 feet bgl
3. Summarized sieve analysis data:

	Average	Range
(i) D50(microns)	347	225-670
(ii) D40/D90	3.1	2.22-4.63
(iii) Kgs (USgpd/ft^2)	189	120-220

(iv) Production well data:

1. TD 504 feet
2. Well casing to 250 feet bgl (140 feet below swl)
3. Screen length 173 feet
4. Specific capacity 6.87 US galls/min/ft = 1.42 litres/sec/m.
5. Well efficiency 54-60%

(v) Site conditions

1. Non responding section upper, from water table (110 feet bgl) to 240 feet bgl (130 feet). Clay layers less than 10 feet thick and 3 in number
2. Responding section: 240-502 feet bgl, (262 feet)
3. Non responding section lower: 502-633 feet bgl, (131 feet)

(vi) Observation wells

1. Three oil company wells screened in upper part of responding section.
2. 01 with packer/pressure transducer system and separated screens set in both upper and lower non-responding sections.
3. 02 with screens set in responding section.

(vii) Aquifer test

1. Five days duration at 749 US galls/min (47.26 litres/sec).
2. All observation wells showed barometric efficiency in range 34-40%.
3. Response artesian with negligible drawdowns in upper and lower non-responding sections.
4. Results of analyses of separate observation wells give comparable transmissibility of between 335-375 m^2/day for responding section.
5. Average permeability of responding section based on pumping test data is in range 4.2 - 4.7 m/day.
6. Average permeability of responding section based on grain size data is 4.8 m/day.
7. Permeability of medium sands averages 6.15 m/day and of fine sands 3.06 m/day.

A general summary of the aquifer test results and site conditions is given above. The production screen is set within the PMM only and was not carried to the base of the LMM, Zone 'a', since the latter consists here largely of fine grained calcareous sandstones. It would be necessary to drill a further 245 feet below base Zone 'a' to reach Zone 'c' of the LMM which is the next possible productive section.

The aquifer testing results from the four observation wells screened in the responding interval are comparable. The average permeability of the responding interval based on the calculated transmissibility and thickness is closely similar to that derived from grain size analysis which suggests that the component sands are largely uncemented. This is confirmed by the flow velocity log (Figure 5, Appendix 1) which shows reduced productivity in the sections with low grain size permeability.

To determine the total transmissibility to the base of the LMM, Zone 'c', the results require to be extrapolated. Since the aquifer test data has shown that the grain size permeability is comparable to the pumping test results, the average grain size permeability for the unconsolidated sands is used multiplied by total saturated thickness and also by a correction factor (0.8). The transmissibility of the LMM Zone 'a' which includes appreciable amounts of calcareous cemented material is more difficult to resolve. Results elsewhere have indicated that a permeability which is approximately 50% of the grain size value may be appropriate. In the case of Zone 'c', no samples are available but the log porosities look comparable to those in Zone 'a' and so a comparable permeability has been used. Details of computation are shown in Table 12.

TABLE 12

Calculated total transmissibility at T(U1-65) to base of Zone 'c', LMM

	1	2	3	4
PMM	362	518	0.8	102 445
LMM Zone 'a'	111	189	0.5	10 395
LMM Zone 'c'	165	189	0.5	15 592
				188 432 $=2340m^2$/day

Columns:-

1. Saturated thickness of permeable section in feet
2. Grain size permeability in US gpd/ft^2
3. Correction factor
4. Transmissibility in USgpd/ft

5.4.2.2 Site T(FF1-65): Figure 5, Appendix 2

(i) Location: northern Phase 2
(ii) Static water level: 90 feet bgl
(iii) Site stratigraphy and lithology

(a) PMM: 0-454 feet bgl; medium and fine sands, some thin interbedded clays and some sandstone.

1. Saturated thickness: 364 feet
2. Sampled 110-460 feet bgl
3. Summarised sieve analysis data:

	Average	Range
(i) D50(microns)	582	360-1150
(ii) Cu	3.51	2.41 - 4.58
(iii) Kgs (USgpd/ft^2)	347	140-780

(iv) Production well data:

1. TD 557 feet
2. Well casing to 356 feet bgl (266 feet below static water level)
3. Screen length - 164 feet
4. Specific capacity: 4.78 US galls/min/foot = 0.99 litres/sec/m
5. Well efficiency: 24-27%

(v) Site conditions

1. Upper non responding section: 90-350 feet bgl with two main sub-sections bounded by clay layers between 10 and 13 feet thick.
2. Responding sections:
   1. 350-454 feet bgl (104 feet)
   2. 475-575 " " (100 feet)

(vi) Observation wells

1. Three Company water wells in responding section 1.
2. 01 with dual screens separated in casing by packer and outside casing with cement plugs; upper screen in lower level of NRS; lower screen in RS. 2.
3. 02 with screens straddling RS1.

(vii) Aquifer test

1. Preliminary airlift test showed Company wells West and Central within same responding interval.
2. Test 1 with full screen and pumping at 622 US galls/min (39. 3 litres/sec) for one day with specific capacity 4. 78 US galls/min/ft.
3. Test 2 with screen backfilled to base PMM and pumping at 358 US galls/min (22. 6 litres/sec) for 5 days with specific capacity of 4. 07 US galls/min/ft.
4. Response artesian but minor inflow from non-responding sections. Note in Test 2, RS. 2 becomes non-responding.
5. Transmissibility of RS.1 calculated at 317 m^2/day and average permeability of sand sections is 10 m/day. Compares closely with average grain size value for identical section of 12. 3 m/day.
6. Permeability of sandy carbonate in RS. 2 in range 3. 3 - 4. 3 m/day using flow velocity data and assumed responding interval of 70-100 feet. Grain size permeability 6. 9 m/day i. e. approximately doubled. Cementation Factor = 0. 5. Transmissibility of RS. 2 using lower permeability equals 100 m^2/day or 8052 US gpd/ft. Total transmissibility both sections of 417 m^2/day with calculated well efficiency of 24%.

The good comparison of the average grain size and pumping test analyses for the upper responding section confirms the validity of the results despite the anomalously low well efficiency. This low value cannot readily be accounted for since the screened section was supposedly drilled with Revert mud. If the well should ever be put into production, the use of a standard mud dispersant is to be recommended for improved development.

The permeability of the sandy carbonate rocks in Zone 'a' of the LMM based on flow velocity data is appreciably lower than the grain size value giving a Cementation Factor of 0. 5 (i. e. (K) true permeability = Kgs) grain size permeability times Cementation Factor (C); or K = C. Kgs.

Total transmissibility is calculated on the basis of the grain size permeability, thickness and a factor depending mainly on cementation. In the unconsolidated sands, a factor of 0. 8 is used which is a rather arbitrary figure but does in this instance correspond to the reduction of the grain size value to the aquifer test permeability. In the cemented sandy carbonates of Zone 'a' a cementation factor of 0. 5 is used based on flow velocity data. Some uncertainty exists as to the best procedure for the section between 190 and 330 feet bgl which has a generally low although variable porosity (very 'peaky' neutron log). The grain size permeability of the upper section (see Table V, Appendix 2) is low and the D50 values are low, both features being in accord with the low porosity and not necessarily implying cementation. The lower half has higher permeabilities and D50 sizes but log porosities are of a similar order. Sandstones are also referred to in the Company lithological log. For this section a factor of 0. 65 has been used. No samples are available for Zone 'c' and a permeability equivalent to that in Zone 'a' has been used on the basis of comparable porosity. Details of the calculation are given in Table 13.

TABLE 13

Calculated total transmissibility at T(FF1-65) to base of Zone 'c', LMM

	1	2	3	4
PMM unconsolidated	214	346	0. 8	59 235
PMM consolidated	120	362	0. 65	28 236
LMM, Zone 'a'	159	239	0. 5	19 000
LMM, Zone 'c'	84	239	0. 5	10 038
				116 539
				=1447 m^2/day

Columns:-

1. Saturated thickness of permeable section in feet.
2. Grain size permeability in US gpd/ft^2.
3. Reducing factor.
4. Transmissibility in US gpd/ft.

5.4.2.3 Site T(T2-65): Figure 5, Appendix 3

(i) Location: south-central Phase 2.
(ii) Static water level: 117 feet bgl.
(iii) Site stratigraphy and lithology:

(a) PMM: 0-390 feet bgl; sands uniform medium to fine with thin interbedded clays.

1. Saturated thickness: 273 feet.
2. Sampled section: 180-390 feet bgl (210 feet feet).
3. Summarised sieve analysis data:

	Average	Range
(i) D50 (microns)	403	280-540
(ii) Cu	2.78	2.57-3.27
(iii) Kgs (USgpd/ft^2)	215	110-310

(b) LMM, Zone 'a': 390-558 feet bgl; medium to fine sands, some sandstones, sandy carbonates and clays.

	Average	Range
(i) D50 (microns)	373	193-525
(ii) Cu	2.71	2.03-3.65
(iii) Kgs (US gpd/ft^2)	315	220-430

(c) LMM, Zone 'c': 681-860 feet bgl.

1. Saturated thickness: 179 feet
2. Sampled section: 690-860 feet bgl (170 feet)
3. Summarised sieve data:

	Average	Range
(i) D50 (microns)	325	205-515
(ii) Cu	3.22	2.15-5.13
(iii) Kgs (US gpd/ft^2)	245	150-400

(iv) Production well data T(T2-65)P.

1. TD: 557 feet bgl.
2. Casing: 299 feet bgl (182 feet bswl)
3. Screen: 192 feet in 257.5 feet section
4. Specific capacity (120 hours): 15.93 USgalls/min/ft (3.3 litres/sec/metre)
5. Well efficiency:
   (i) 21% based on pumping test transmissibility
   (ii) 79% based on grain size and flow velocity data

(v) Site conditions

1. Non responding sections upper (2): 117-289 feet bgl (172 feet)
2. Responding sections:
   (i) 289-413 feet bgl (124 feet)
   (ii) 413-558 feet bgl (145 feet)

(vi) Observation wells

1. Three Company water wells at T2-65 screened in RS. 2
2. One Company water well at T1-65 screened in RS. 2
3. 01 upper screens in RS. 2 (lower screens backfilled)
4. 02 (long string) in RS. 1
5. 02 (short string) in lower NRS.

(vii) Aquifer test

1. Five days duration at 1609 US galls/min
2. Response artesian at all screened levels including non-responding section, although drawdown in latter very small
3. Calculated transmissibilities from different observation wells data all comparable
4. T. of RS. 2 equalled 1421 m^2/day equivalent to average permeability of 32.15 m/day. Average grain size permeability is 12.8 m/day (315 US galls/day/$ft.^2$)
5. T. of RS. 1 equalled 1075 m^2/day equivalent to average permeability of 28.45 m/day (cf. grain size value of 8.76 m/day or 215 US galls/day/$ft.^2$
6. Total T. of responding section is 2496 m^2/day with storage coefficient of $2.0 + 10^{-4}$
7. Corresponding well efficiency: 21%

(viii) Lithological Analysis

1. T. of RS. 1: 270 m^2/day (Table 14)
2. T. of RS. 2: 339 m^2/day
3. Combined T of total RS.: = 609 m^2/day
4. Corresponding well efficiency: 79%

(ix) Fibre-glass test well

1. TD: 848 feet bgl
2. Well casing: 324 feet bgl (207 feet bswl)
3. Screen: 241 feet in 524 feet interval. Details as follows:

(i) 324-386 feet bgl	(62 feet)	- in	PMM
(ii) 426-525 feet bgl	(99)	- "	LMM, Zone 'a'
(iii) 705-746 " "	(41)	- "	LMM, Zone 'c'
(iv) 786-825 " "	(39)	- "	LMM, Zone 'c'

4. Specific capacity after demudding with tetra sodium pyrophosphate: 33.76 US galls/min/ft. (Data supplied by Tipton and Kalmbach)
5. Specific electrical conductance: 1710-1740 micromhos at 25°C during pumping test

(x) Stratigraphy and lithology

1. LMM, Zone 'c': 688-834 feet bgl
2. Saturated thickness: 146 feet
3. Sampled section: 690-840 feet bgl (150 feet)
4. Summarised sieve data:

	Average	Range
(i) D50 (microns)	341	205-515
(ii) Cu	3.06	2.47-4.41
(iii) Kgs (US gpd/ft^2)	247	150-400

(xi) Aquifer test 2

1. Conducted during development pumping discharge from RS1 and RS2 computed by flow velocity log as 35.5 litres/sec (507 US galls/min)
2. Discharge from RS.1: 11.83 litres/sec
3. Discharge from RS.2: 20.15 litres/sec
4. T. of RS.1 from match point data: 631 m^2/day
5. T. of RS.2 from match point data: 650 m^2/day

The apparent well efficiency of the first well T(T2-65)P, based on the aquifer pumping test transmissibility is anomalously low even allowing for poor well development. Additionally the calculated permeability is considerably in excess of the grain size value and also much higher than known elsewhere in the aquifer. There seems little doubt that the pump test transmissibility is grossly exaggerated but the explanation is not easy to find.

Transmissibility calculated on the basis of grain size and flow velocity data provides a considerably reduced value of T. and a correspondingly increased value of efficiency (79%). The efficiency is comparable to the Phase 1 production wells but is appreciably higher than both the two completed Phase 2 production wells. Despite these conflicting features, the transmissibility calculated from the grain size data is regarded as more realistic. Water quality results as well as drawdown data indicates that the lower NR section might more realistically be incorporated into the upper responding section (1). This assumption would increase the total transmissibility of the responding section and decrease the apparent well efficiency to 63%. Details are shown in Table 14 below. This value is comparable with the computed efficiency of T(U1-65)P.

A second test well T(T2-65)FG was drilled at the site by request of the consultant engineers, Messrs Tipton and Kalmbach. This well was designed to test the deeper aquifer unit (Zone 'c' of LMM), additionally to higher levels. It was drilled with Quiktrol mud and completed with slotted fibre screen and emplaced gravel pack. Screening extended over approximately the same zones as in T(T2-65)P plus Zone 'c' of the LMM. Following normal development with swabbing and airlifting, a pumping test was run with measurements of discharge being made on the surface and in the well as far down as the base of Zone 'a' (because of insufficient length of cable to the flow meter), combined with drawdown observations in the same observation wells as before excluding the Company well at (T1-65). During this test, the specific capacity was in fact lower than in T(T2-65)P despite the increased length of screen. Observations were made by Kufra and Sarir Authority Geologists and basic data including match points on plotted drawdown curves sent back to London. Using the match points in association with flow velocity data to obtain discharge from the appropriate responding intervals, calculated transmissibilities are shown in section (xi). The values are appreciably lower than those derived from Test 1 but still higher than the grain size values.

This initial test was carried out prior to proper demudding of the aquifer but the flow velocity graph showed a closely comparable percentage plot to that from the first well over the same section. This may mean that the effects of the mud infiltration are proportional and not necessarily that the first test well required demudding, although this is still a possibility.

Extrapolation of the sieve data to obtain total transmissibility of the Post-Eocene sequence to the base of Zone 'c' LMM is shown below.

TABLE 14

Calculated total transmissibility at T(T2-65) to base of Zone 'c', LMM

	1	2	3	4
PMM NRS.1	100	227	0.9	20 430
NRS.2	58	206	0.9	10 753
RS.1	106	228	0.9	21 751
Total				52,934 = 657 m^2/day
LMM Zone 'a'				
Sands	61	333	0.9	18 282
Sandy carbonates etc	81	287	0.44	10 228
				28 510 =354 m^2/day
LMM Zone 'c'	103	247	0.8	20 352 =253 m^2/day

Total Transmissibility: 101 796 = 1264 m^2/day

Columns:-

1. Saturated thickness of permeable section in feet
2. Grain size permeability in US gpd/$ft.^2$
3. Correction factor
4. Transmissibility in US gpd/ft.

The PMM is regarded as completely unconsolidated and the correction is negligible.

In LMM, Zone 'a', sandy clays were included with sandy carbonates since the flow velocity log indicated similar production from both materials. The correction factor of 0.44 is based on the flow velocity log to obtain relative permeability as compared with the sands. A slightly different calculation has been used to that in Table IX, Appendix 3 which gives a slightly increased value of transmissibility for this zone (354 m^2/day as compared with 328).

On the assumption that the well screen in the second test well T(T2-65)FGW, is responding to the NRS. 2 and RS. 1 of the PMM, RS. 2 (= Zone 'a', LMM) and Zone 'c', LMM, a well efficiency of 98% corresponds. Gravel packed wells have certainly been shown to be more efficient and the well has additionally been subjected to a thorough development including acidising. Nonetheless, the very high value does suggest a somewhat underestimation of total transmissibility. Alternatively the specific capacity may be over valued although there is no apparent reason to suppose that this is so.

5.4.2.4 Site T(PI-65)

1. Location: southern Phase 2
2. Static water level: 194 feet below ground level
3. Site stratigraphy and lithology:

(a) PMM: 0-243 feet bgl; mainly sands with sandy carbonate near base.

1. Saturated thickness: 44 feet
2. Sampled section: 200-240 feet bgl
3. Summarised sieve analysis data:

	Average	Range
(i) D50 (microns)	309	238-338
(ii) Cu	2.72	1.77-3.06
(iii) Kgs (US gpd/ft^2)	258	200-360

(b) LMM, Zone 'a': 243-388 feet bgl; medium sands interbedded with clays and sandy carbonates

1. Saturated thickness: 145 feet
2. Sampled section: 240-390
3. Summarised sieve analysis data:

	Average	Range
(i) D50 (microns)	353	296-620
(ii) Cu	2.91	2.16-3.68
(iii) Kgs	259	190-370

(c) LMM, Zone 'b': 388-559 feet bgl; interbedded clays/sandy clays and sands with subordinate sandy carbonate.

1. Saturated thickness: 171 feet
2. Sampled section: 80 feet interspersed samples
3. Summarised sieve analysis data:

	Average	Range
(i) D50 (microns)	357	270-520
(ii) Cu	3.00	2.31-4.06
(iii) Kgs (US gpd/ft^2)	233	185-340

(d) LMM, Zone 'c': 559-729 feet bgl; mainly sands with subordinate sandstones and sandy carbonates and clays.

1. Saturated thickness: 147 feet
2. Sampled section: 560-730 feet bgl
3. Summarised sieve data:

	Average	Range
(i) D50 (microns)	246	185-320
(ii) Cu	2.43	1.78-3.50
(iii) Kgs (US gpd/ft^2)	225	145-320

TABLE 15

Calculated total transmissibility at T(P1-65) to base of Zone 'c', LMM.

		1	2	3	4	5
PMM	(i)	32	277	0.8	7091	Sands
	(ii)	12	200	0.5	1200	Sandy carbonate
LMM 'a'	(i)	72	268	0.8	15436	Sands
	(ii)	33	223	0.5	3679	Sandy carbonate
LMM 'b'	(i)	63	238	0.8	11995	Sands
	(ii)	35	245	0.65	5574	Sandstones
LMM 'c'	(i)	124	212	0.8	21030	Sands
	(ii)	29	195	0.65	3675	Sandstones
					69680 = 865 m^2/day	

Columns:-

1. Saturated thickness of permeable section in feet
2. Grain size permeability in US gpd/ft^2
3. Correction Factor
4. Transmissibility in US gpd/ft
5. Significant lithology of permeable section

5.4.2.5 Site T(H1-65)

A single observation well has been drilled at this site to 1480 feet bgl. Full details are not currently available* in London but on the basis of the lithology and the water quality, it was decided not to drill a production well at the site. The oil exploration well H1-65 was drilled during the early period of exploration in this Concession and the associated geophysical logs and records are not good. It is unfortunate also that no geophysical logs could be run in the recently drilled test hole. Full details of the sieve analysis data are available in the records and a summary of certain relevant sections is included below.

1. Location: southern Phase 2
2. Static water level: 221 feet bgl
3. Site stratigraphy and lithology:

* October 1974

(a) PMM: 0-260 feet bgl; Fine sands and sandy carbonates, the latter including most of the saturated section. It is possible that the base of the PMM may have been misidentified here.

1. Saturated thickness: 49 feet
2. Sampled section: 220-250 feet bgl
3. Summarised sieve analysis data:

	Average	Range
(i) D50 (microns)	387	380-390
(ii) Cu	1.37	1.35-1.40
(iii) Kgs (US gpd/ft^2)	333	300-400

(b) LMM, Zone 'a' 260-350 feet bgl; sandy carbonates and medium sands.

1. Saturated thickness: 90 feet
2. Sampled section: 230-250 feet (250-300 not sieved due to high proportion of carbonate)
3. Summarised sieve data from 300-350 ft bgl

	Average	Range
(i) D50 (microns)	358	290-440
(ii) Cu	1.51	1.20-1.8
(iii) Kgs (US gpd/ft^2)	308	220-400

(c) LMM, Zone 'c' 380-530 feet bgl; fine sands and some sandstone

1. Saturated thickness: 150 feet
2. Sampled section 380 to 530 feet bgl
3. Summarised sieve analysis data:

	Average	Range
(i) D50 (microns)	239	205-300
(ii) Cu	2.09	1.75-2.20
(iii) Kgs (US gpd/ft^2)	180	140-225

TABLE 16

Calculated total transmissibility at T(H1-65) to base of Zone 'c', LMM

PMM	49	333	0.5	8159
LMM, Zone 'a'	34	308	0.5	5236
	51	308	0.8	12566
LMM, Zone 'c'	125	184	0.8	18400
	21	163	0.5	1712
				46073
				= 572 m^2/day

Columns:

1. Saturated thickness of permeable section in feet
2. Average grain size permeability in US gpd/ft^2
3. Correction factor
4. Transmissibility in US gpd/ft.

WATER RESOURCES OF THE PHASE 2 AREA

The total resources of water in an aquifer is the volume represented by the product of area, saturated thickness and an appropriate storage factor. The available resources within a defined area such as the Phase 2 can be most realistically assessed in terms of practical well-fields in which an appropriate abstraction from suitably spaced wells is related to all significant aspects such as long-term interference and pumping drawdowns and water quality variations within the aquifer. Actual well locations will also depend upon factors additional to hydrogeological considerations. Predictive drawdowns for alternative well field patterns are, in the case of an extensive field with large numbers of wells in an irregular array and within a complex aquifer, best evaluated by a computer model incorporating the variations in aquifer parameters and the response boundary conditions.

For the Nubian aquifer in the southern Phase 2 available information is limited and modelling not justified. Detailed models have been prepared for the PMM aquifer in the Phase 1 Area. These have included a steady-state model in which the form of the water table is correlated with variations in transmissibility and inflow and outflow; and unsteady-state models which assume either water table or leaky artesian responses and to which various abstraction schemes have been applied. It was found that with the appropriate parameters used relating to leaky artesian response i.e. vertical permeability and thickness of leaky layer, the two conditions modelled gave closely similar long-term predictions. Similar models for the Phase 2 Post-Eocene squifer system are also planned and have been initiated but not completed. The reasons relate mainly to the increased complexity of the aquifer system and the insufficient degree of information due principally to delays in drilling. The omission is unfortunate but since the most critical aspects of aquifer response are still unknown, no significant delay in well field development need be incurred provided a model can be completed shortly.

The model commissioned by Tipton and Kalmbach for their designed well field in the Phase 2 Area assumes an average transmissibility of 1000 m^2/day and a water table response with a specific yield of 0.15. The predicted drawdowns could be appreciably in error if the response assumption proves unjustified. Every effort should therefore be made to ascertain the response in the area of interest. It is understood that the first 50 wells are expected to be completed by the end of 1974. The first six sites are scattered and have each two associated piezometers to permit pumping tests to be carried out. It is further recommended that the remaining 44 should not be grouped with the close spacing (d) of the design field which assumes a water table response. Provided a spacing of 'n' times 'd', is used, additional wells can be eventually drilled between initial wells if the results of the aquifer testing justify.

Pumping tests at the first 6 sites should be carried out as soon as possible and preferably for a fairly long duration provided that any effects due to recycling can be recognised and accounted for. The observation piezometers include one in each set of two which is screened at the water table and designed to measure the longer term effects of eventual drawdown of this surface.

6.1 Water Resources of the Nubian Aquifer in the Phase 2 Area

The Nubian aquifer occurs at moderate depths in the southern Phase 2 Area but dips steeply to the north below the Sirte Basin Marine Cretaceous and Tertiary successions. The Nubian thickens southwards into the main Kufra Basin. The Post-Eocene sequence above the Nubian in the southern Phase 2 progressively reduces southwards. The piezometric surfaces map (Figure 22) shows that to the north of 26°00N, the Nubian aquifer is confined with a higher piezometric head than in the overlying Post-Eocene. Southwards, the piezometric surfaces must converge since a short distance to the south, the Nubian outcrops.

Other than the oil exploration wells at A1 and D1-71, no wells penetrate the Nubian in the southern Phase 2 Area. At A1-71, the Tertiary sequence includes approximately 500 feet of sands and sandstones, presumably Post-Eocene, and 290 feet of marl and dolomite (? Eocene/Palaeocene) overlying 1982 feet of sandstone considered by Oasis geologists to be Nubian. The sandstone overlies shales dated by Climagraptus as Silurian. At D1-71, the predominantly arenaceous sequence overlying Silurian shales is not differentiated in the Company log.

Groundwater development in the vicinity of Tazerbo Oasis to the west and south of A1-71 is proposed and although a detailed resources analysis is clearly not feasible, it is appropriate to consider some aspects of the characteristics and and likely response of the underlying aquifers. This discussion is primarily concerned with the Nubian but some consideration must be given to the Post-Eocene which includes several hundred feet of saturated formations reducing southwards in thickness. If the characteristics of the Post-Eocene sequence are maintained from the area immediately to the north (F1/H1-65), the component sands are likely to be fine grained to silty with corresponding low permeability. Production wells may need to be completed in both Post-Eocene and Nubian, even where the former includes an appreciable thickness. The aquifer response would be complex. The Nubian would presumably respond in artesian fashion, changing in time to leaky artesian or water table either in consequence of leakage from above or when the cone of depression attains the unconfined Nubian outcrop to the south. The variable response of wells in this area could have significant effects on well-field performance and the nature of the response would need to be determined in the initial production wells. The Nubian dips steeply to the north and north-west and locally wedges out against Basement and older Palaeozoics. Both these circumstances will result in boundary effects on hydraulic drawdown.

Water quality is likely to be fresh in the Nubian in the southern Phase 2 as indicated by the wells at Bzema and Rebiana to the south and the flowing artesian well at C1-71. There is a marked deterioration northwards and this feature will need to be taken into account in relation to any proposed large scale development. Water quality in the Post-Eocene sequence is likely to be more variable but is generally good in the vicinity of Tazerbo Oasis (Table 7).

6.2 Water Resources of the Post-Eocene in the Area.

The Post-Eocene sequence in the Phase 2 is a variable assemblage of sands and clays with subordinate sandstones, sandy carbonates and carbonates. Both total and saturated thickness increase towards a central north-south trending axial trough where the latter locally attains 2,800+ feet. In the deepest part of the trough which occurs mainly in the eastern half of the Phase 2, the lithological sequence includes thick clay horizons separating predominatly arenaceous formations above and below. In marginal areas to south, east and west, clay percentage decreases and sand increases.

The water resources of this sequence are obviously large. Even in the central axial region where clays form a significant percentage, more than half the total saturated thickness is composed of fine to medium grained, generally unconsolidated sands of probably high porosity.

Detailed information on water quality is mainly available for the upper levels of the sequence which include the PMM and the LMM, Zone 'a'. Over much of the Phase 2 Area quality in this interval is fair to good, with electrical conductances less than 3000 micromhos at 25°C. Deterioration is apparent on the eastern margins and particularly so to the north-east. Quality also appears to deteriorate south of latitude 27°00'N but information is not extensive. A deterioration is also known to occur in the central Phase 2 Area in the highest levels of the aquifer close to the water table. Evidence of the extent of this latter occurrence is not known with certainty but some indications are that it may be fairly localised and relatively thin.

From the point of view of development, the Post-Eocene sequence in the main Phase 2 may be subdivided into a shallow aquifer to the base of Zone 'c' of the Lower and Middle Miocene and a deep aquifer which would include Zone 'e' of the LMM and Zone 'a' of the Oligocene. Each main Stratigraphic unit will be discussed briefly before a fuller discussion of potential development in the shallow aquifer system.

6.2.1 Oligocene

The Oligocene is predominantly an arenaceous unit with saturated thickness in the northern Phase 2, in the range 800/1300 feet. Clay percentage generally increases in the lower half and the grain size of the associated sands becomes finer grained. Confirmation of the presumed lower permeability at the lower levels was provided in the test pumping at T(Q1-65) when no production could be obtained from the related screen interval in the test well. At this same site, water quality in the Upper Oligocene proved to be fresh with specific electrical conductance less than 3000 micromhos. From a cursory survey of the SP logs, general water quality in the Oligocene seems likely to be fair to good in the more southerly and westerly Phase 2 areas but may deteriorate in the north-east.

The Oligocene is not scheduled for current development but it would seem advisable to obtain further information at a reasonably early stage. A second deep test hole has been commenced in the central axial region at Y1-65. The Oligocene would respond to abstraction in artesian fashion. The bulk of the formation appears to consist of unconsolidated sands and a good approximation to permeability should be possible from lithological sample analysis.

6.2.2 Lower and Middle Miocene

Five subdivisions or zones numbered 'a' to 'e' have been recognised, two of which in the central basin area are predominantly of clay. Towards the marginal areas, sand percentages increase replacing clay. The total thickness in the main Phase 2 north of 27°00N is in the range 500 - 1300 feet, the greater part of which occurs below the wster table. The LMM outcrops in the south-west. Zones 'a', 'c' and 'e' are predominantly arenaceous but commonly include a significant percentage of consolidated material and particularly to the north grade into sandy carbonates and carbonates. Porosity and permeability are correspondingly lower than equivalent unconsolidated sands. Zone 'a' and to a lesser extent Zone 'c' are likely to respond on long term abstraction in leaky artesian fashion and zone 'e' in artesian fashion. Water quality is known to be good in the higher zones in the central Phase 2 and also in the lower levels in western marginal areas (cf T(Q1-05). Deterioration is to be expected to the north-east and SP logs can provide the general details.

6.2.3 The Calanscio Formation (Post Middle Miocene

This unit has a more limited occurrence than the other two groups and a lower saturated thickness, a maximum of about 350 feet in the north-east progressively reducing to south and west. It is predominantly arenaceous and unconsolidated and of generally coarser grain size and higher permeability than the other arenaceous formations. Despite its relatively low thickness, its high permeability and accessibility make it one of the most significant formations in the Post-Eocene. The lower levels of the Calanscio Formation appear locally at least to be rather finer grained than the upper and in consequence of lower permeability. This has a certain practical significance as will be discussed later. Water quality in the PMM is fair to good over much of its occurrence in the Phase 2 but some deterioration occurs locally in the highest levels near the water table and also in the eastern marginal areas.

6.2.4 Well Field Development

6.2.4.1 Location and Planning

Present planning envisages initially an

irrigation scheme requiring 2½ million m^3/day to irrigate 50 000 hectares. The proposed area of development is based upon soil and terrain considerations and occupies a belt some 30 - 40 km wide and 130 - 140 km long extending in a north-south direction west of the main Calanscio Sand Sea and between the latitudes of 26°45' and 28°00' North. The method of irrigation proposed is to be the same as that at Kufra consisting of a central well supplying water to a pivot machine rotating over a circular area of approximately one km diameter. The required five hundred wells are sited along two main and two subsidiary lines. The location of the field and the provisional design and spacing of the wells have been prepared by Tipton and Kalmbach on the basis of hydrogeological information available in early 1974 and on the results of the soil surveys carried out by this same organisation. Preliminary analysis of the results of test drilling indicated that the area to the south of 27°30'N is more favourable and the initial 50 wells planned for 1974 and sufficient for a pilot project of 5000 hectares are to be located in this restricted section. The analytical work associated with the preparation of this report throws some doubt on the conclusions of the preliminary analyses and the aspect is discussed below.

The production wells for this scheme are required to abstract from the shallow aquifer unit and to be less than 1000 feet total depth. In effect this means that production will be limited to the Post-Middle Miocene and Zones 'a' to 'c' of the LMM.

The location of this well-field is not necessarily the optimum from purely hydrogeological considerations but it is assumed that in relation to insitu irrigation requirements, factors of soil and terrain have imposed certain restrictions. On general hyraulic considerations, wells are better aligned along the strike rather than as here down the dip of the hydraulic gradient. The location is favourable in that it occurs in the area of maximum thickness of the most permeable and accessible of the formational units - the PMM, but less favourable in relation to the immediately underlying LMM. The latter has a high clay percentage in the axial region and in the more northerly part, both Zone 'a' and Zone 'c' of the LMM are likely to be poorly productive, consisting as they do of predominantly sandstones and calcareous sandstones grading to sandy carbonates.

From water quality considerations, the well field is located in a part of the aquifer containing good quality water but a deterioration does occur immediately to the east and more significantly so to the north-east. Deterioration also occurs in the highest levels near the water table but this could be a localised effect. These various and sometimes opposing considerations require compromise decisions which are difficult to make without adequate quantitative control. No detailed comment can be made on the advantage of alternative locations as the restricting factors on irrigation requirements are not known to the writer. On the assumption that the location is necessarily generally restricted to that selected, with marginal modifications only being possible, it does point to the need to be particularly flexible in the early stages of well construction and spacing. The most appropriate depth to drill at any location can be determined from the maps provided with this report and taking due consideration of the lithological trends as described. At the same time, it is worth drilling a selection of the initial wells at scattered locations to maximum depths in order to confirm by actual pump tests and flow meter logging the indications of the basic geological studies.

6.2.4.2 Well Spacing and Design in relation to Aquifer Response

Wells screened at several selected intervals in the upper Post-Eocene sequence will respond in complex fashion. The deeper horizons such as Zone 'c' may have a relatively long-term artesian response since the clay horizons comprising zone 'b' of the LMM are thick and relatively extensive. Being essentially marine clays, at least in the north, permeability is likely to be low. The PMM and the LMM Zone 'a' will respond initially in artesian fashion as shown by the three tests conducted to date but in view of the small thickness and perhaps moderate permeability* of the interbedded clays, the response will probably change to leaky artesian after a fairly short period of time.

The complex response of the aquifer related in some instances to the type of completion, will affect aspects such as the specific capacity, and the evolution of the cone of depression. Cones of depression may develop differently in different horizons depending on varying transmissibilities and the nature and degree of inter-action with adjacent horizons.

Total interference drawdowns will relate therefore to one or more piezometric surfaces depending on their degree of independence. Flow movements at certain levels may be relatively rapid and the cone of influence wide such as where

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*Clays in the fluviatile PMM are sandy and, according to data from the Phase 1 Area, are likely to be inextensive. Their supposed origin, as overbank deposits indicates moderate permeability within the clay range of values.

the transmissibility is high and the response artesian; elsewhere, movements could be retarded in relation to poorly permeable formations. These aspects might be critical in long term water quality variations.

The selection of screen and casing length in this type of sequence requires a compromise decision. Specific capacity will relate mainly to the transmissibility of the responding interval (s) in which the screen is set. Improvements in the specific capacity may be obtained by further development of the screened intervals or by drilling deeper if the underlying formations are suitable. Increasing the screen length by decreasing the well casing is also possible but in so doing the total available drawdown is reduced. This includes both pumping and interference drawdowns, the latter relating as described above, in complex fashion to total transmissibility and the nature of the aquifer response expressed in terms of vertical as well as horizontal components of flow and specific yield, additionally to well spacing and total abstraction. The significance of the inter-relationships may be appreciated by considering the situation in the northern Phase 2 Area. The upper levels of the Calanscio Formation have higher permeability than the lower levels. Wells screened in the lower levels will have a relatively low specific capacity (cf T(U1-65)P and T(FF1-65)P).

In view of the likely poor productivity of the potential aquifer occurring at moderate depths at this location (Zone 'c'), the question must be considered as to whether it would be possible to improve the specific capacity by reducing casing length and increasing screen but thereby reducing available drawdown. The possibility is worth considering if thereby sufficient production can be gained from such a well to conform with the required production rates for the proposed irrigation unit. It may be necessary however to increase the well spacing to reduce interference drawdown. This aspect will need to be considered in relation to possible development in the northern Phase 2 Area.

These relations can be expressed quantitively in terms of T(U1-65)P and T(FF1-65)P. Design irrigation requirements are for a production of 66 litres/sec which is approximately equivalent to 1050 US gpm. The test production well is screened 146 feet below the water table which thus represents the total effective available drawdown unless a narrow diameter pump can be installed in the screen section. The transmissibility of the lower PMM derived from the pumping test is 26 974 US gpd/ft and the observed specific capacity 7 galls/min/ft representing 60% efficiency. For the purpose of the following discussion, it is assumed that a well efficiency of 65% is possible by adequate development. On the basis of design requirements, a specific capacity of 7 galls/min/ft implies a pumping drawdown of 150 feet at 1050 US gpm which gives no allowance for interference drawdown much less for any reduction in specific capacity. Deepening the well to the base of Zone 'c' will improve specific capacity and provisional calculations are as follows:-

Transmissibility lower PMM =	26 974 US gpd/ft
LMM, Zone 'a' =	10 395
LMM, Zone 'c' =	15 592
Total transmissibility	52 962

These values are based on extrapolated results as described in an earlier section. The specific capacity after 1000 hours on this assumed transmissibility is 20 US gpm/ft and with 65% efficiency, the actual value would be 13 US gpm/ft.

A period of 1000 hours is selected for the calculation of specific capacity on the basis that quasi-steady state conditions will have been attained by that time in consequence of leakage. In practical terms since there is no recharge, specific capacity will continue to fall at a very low rate. The eventual specific capacity of 13 US gpm implies a pumping drawdown of 80 feet at the design rate with a consequent available 66 feet of interference drawdown. The spacing of the wells in relation to the total abstraction and aquifer response will require to be such that this amount of interference drawdown is not exceeded in the design period. An improvement of specific capacity could be obtained by increasing the screen length upwards at the expense of the well casing. The upper levels of the PMM are more permeable than the lower and a provisional calculation is shown below on the assumption of an additional 30 feet of screen and assuming the increase of transmissibility is equivalent to thirty times the average permeability of the section between 200 and 260 feet. This is thought to be a conservative estimate to offset partial penetration effects. The new effective transmissibility is 69 792 US gpd/ft and the specific capacity after 1000 hours and assuming 65% efficiency is 17 US gpm/ft. The total available drawdown is 116 feet of which 61 feet is required for the pumping drawdown leaving 55 feet available for interference drawdown. Thus a lower limit of interference drawdown is imposed although with an appreciable gain in specific capacity.

At T(FF1-65), the test well was drilled into Zone 'a' of the LMM and was cased down to 266 feet below the water table. The well efficiency on test was extremely low but there is good confirmation of the transmissibility values by the grain size results and an improved specific capacity is to be expected if further development is carried out. On the assumption of a transmissibility value of 417 m^2/day equivalent to 33 577 US gpd/ft, a 65% efficient well would have a specific capacity of 8 US gpm after 1000 hours. A pumping drawdown of 131 feet would be required leaving 135 feet for interference effects. An improvement of specific capacity could be obtained by extending the screen either down or up. The most logical approach is to determine the limits of expected interference drawdown on the basis of model studies and to select the casing and screen proportions to give the most efficient combination. It is appreciated that in the present circumstances in which production well drilling has commenced prior to a proper evaluation of aquifer performance, it is impracticable to adopt this approach. In the circumstances, it is better perhaps to extend a well downwards and make a generous allowance for interference drawdown. If the initial test production well in a general location gives higher specific capacities than anticipated, or the production from lower levels is negligible, it is then desirable to readjust these proportions and to screen at a higher level.

6.2.4.3 Model Studies

A drawdown simulation of the proposed Sarir well field has been prepared by Tipton and Kalmbach, Inc, January, 1974. The simulation assumes a transmissibility of 1200 m^2/day, a net continuous abstraction of 45 litres/sec (70% of pumping rate) and most significantly an assumed water table response with a specific yield of 0.15. Predicted interference drawdowns in the main well field area after 55 years are in the range 25-35m (80-115 feet). The value of transmissibility is conservative as shown by the data in this report. Specific yield in the predicted cone of depression is likely to be of the order used or possibly more. The most significant uncertainty is the nature of the response which if other than effectively water table would increase the predicted drawdowns.

In the present circumstances, it is difficult to reconcile the various possibilities but it is more realistic to allow for the possibility of greater than predicted drawdowns in planning the well field. On the basis of minimum values of interference drawdown, casing and screen proportions can be selected in the manner described above. Spacing of the preliminary wells should be several times the likely optimum distance. The combinations of results from the initial test wells, both production and aquifer tests, can be used in model preparation and calibration and selection of final spacing.

Some preliminary work has been carried out by the IGS on the preparation of a steady-state model designed to correlate transmissibility and known piezometric gradients. It is assumed that the upper levels of the Post-Eocene to the base of Zone 'c' can be regarded as an independent flow system. Values of transmissibility have been derived at various sites throughout the Phase 2 Area by extrapolating the results of the 3 aquifer tests in accordance with samples and/or geophysical logs. Since 6 sites only have been drilled in the current series of investigations, available lithological information in most cases is limited to company well records. Initially, average values of permeability derived from the pumping test results were assigned to lithological units e.g. sand or clay sand, sandstone, sandy carbonate etc. with no distinction made otherwise. The preliminary plots showed lower transmissibilities in the north than in the central Phase 2, incompatible with the hydraulic gradients. The initial computer runs (prepared by Dr. R. Kitching) quantitatively demonstrated this incompatibility. A fuller and more careful re-evaluation of the site data proved the need to differentiate levels of varying permeability within the main lithological units. A notable distinction for example occurs between upper and lower levels in the PMM. This re-evaluation has formed the basis of the total transmissibility determinations at the 5 test sites quoted in this report and which now show an accord with the hydraulic gradient. Extrapolation of this improved analysis from sampled to unsampled sites is more problematic but the general evidence of continuity of the stratigraphic units in the Phase 2 Area may be a measure of its feasibility. This work has not yet commenced but it is hoped that approval to continue can be obtained.

The data would form the basis for a steady-state model, a preliminary necessity to the production of unsteady-state models to which appropriate abstraction schemes can be applied. The latter type will need to treat the aquifer as a complex unit incorporating both artesian and leaky artesian components. These conditions can be modelled on general theoretical grounds but it should be appreciated that at present only values of horizontal permeability can be assessed with any degree of certainty. The most significant and problematic aspect will relate to the extent and permeability of certain high level clay layers. This information will need to be obtained from the long-term aquifer tests proposed for the initial production wells which have associated piezometers. Until some information bearing on this aspect becomes available, the preparation of an unsteady-state model is severely hindered.

7 SUMMARY AND CONCLUSIONS

7.1 General Geological Occurrence of Main Aquifers.

(i) Two main aquifer systems occur in the Phase 2 Area:- the Post-Eocene and the Nubian. Both are complex systems with their main occurrences in large sedimentary basins, the Sirte and Kufra Basins respectively. The Sirte Basin developed by crustal collapse and subsidence of a basement high. The Basin extends on a main north-south axis and is confined essentially to Libya. The Kufra Basin developed between two structural uplifts; it strikes north-east - southwest and extends into Chad, the Sudan and Egypt and forms part of the larger Nubian Artesian Basin of North East Africa. The Phase 2 Area extends over a large part of the southern Sirte Basin and overlaps marginally into the northern Kufra Basin.

(ii) The main permeable formations in both aquifer systems are arenaceous with maximum saturated thickness in the Phase 2 Area of 2800 feet (Post-Eocene) and 2000 feet (Nubian).

7.2 Nubian Sandstone Series

(i) The Nubian Sandstone Series in the Kufra Basin forms the uppermost member of a sedimentary succession ranging in age from Cambrian to Lower Cretaceous. The Series itself may extend from the Jurassic but it is thought to be mainly Lower Cretaceous. The Palaeozoic formations are mainly arenaceous with subordinate shales and were deposited in continental to marginally marine environments. The Nubian is also predominantly arenaceous with subordinate shales but is considered to be entirely continental (fluvio-limnic) in origin.

(ii) Dips into the Kufra Basin are shallow, generally less than 3 degrees. Formations equivalent at least in part to the Nubian but described in more general terms as Continental Mesozoic Sandstones extend from the Kufra into the Sirte Basin dipping more steeply beneath the thick series of Upper Cretaceous and Tertiary Successions. The passage between the two Basins occurs as a narrow neck between outcrops or shallow subcrops of Palaeozoic rocks. Within the Sirte Basin, the Continental Mesozoic Sandstones occur sporadically overlying or wedge out against former basement highs. Residual occurrences commonly show variable alterations in consequence of the periods of weathering and erosion to which they were subjected to prior to burial beneath younger deposits. Distinction between Mesozoic and Palaeozoic sandstones may not be obvious in subsurface occurrences.

7.3 Post-Eocene Formations

(i) The Post-Eocene in the Phase 2 Area comprises the Oligocene, Lower and Middle Miocene (LMM), and the Calanscio Formation of the Post-Middle Miocene (PMM), as well as surface deposits of more recent origin (dune sands, fossil soils, calcretes etc.).

(ii) The Post-Eocene Formations are the youngest members of the sedimentary succession of the Sirte Basin which range upwards from the marine Upper Cretaceous. The marine Upper Cretaceous includes transgressive sandstones overlain by shales; the Lower Tertiary (Palaeocene and Eocene) are predominantly carbonate (with evaporite) rocks and shales.

(iii) The Sirte Basin has a north-south axis with formations generally increasing in thickness towards the axial line. The feature also accords with the present surface topography which shows a broadly synclinal form of similar trend and suggests that subsidence has continued through to recent times. In the Post-Eocene sequence, older formations occur in marginal area and the youngest, the PMM in the central basin. The outcrop may correspond fairly closely with the original limits of deposition.

(iv) The Lower Tertiary formations (Palaeocene and Eocene) are marine. There was a maximum marine incursion in Eocene times which extended beyond the main boundary of the Sirte Basin mainly to the south and may have reached the Niger Basin.

(v) The Post-Eocene is composed largely of unconsolidated sands with subordinate clays and some calcareous sandstones grading locally to sandy carbonates. Total thickness decreases southwards and to marginal areas away from the main north-south central trough or basin which in the Phase 2 occurs between longitudes 22^{o} and 23^{o} East.

(vi) The stratigraphy of the Post Eocene in the Phase 2 is difficult to evaluate due mainly to lack of fossil evidence. The main subdivisions between the PMM/LMM and the LMM/Oligocene have been traced from the Phase 1 Area where better stratigraphic evidence exists. Various subdivisions of the main stratigraphic units have been recognised mainly on the basis of lithology and relative positions. The various subdivisions, or Zones, show significent lateral variations in lithology.

(vii) A marked lithological changes occurs at the upper boundary of the Eocene. The sequence in the Post-Eocene in the central basin shows a central clay horizon with predominantly arenaceous formations above and below. The central clays are of Lower and Middle Miocene age with the overlying arenaceous unit partly LMM and partly PMM; the underlying arenaceous unit is partly LMM, mainly Oligocene.

(viii) In Phase 2 marginal areas to south, west and east, sands increase at the expense of clays. Relations to east and west of the Phase 2 Area are less well understood, particularly to the east. There the central clays overlap the lower arenaceous unit on to the Eocene and the upper arenaceous unit increases in thickness. It is considered that the changes are more likely to relate to lateral changes in lithology within the main stratigraphic units, rather than overlap of the LMM on to the Eocene.

(ix) The general sequence in the Phase 2 from upper members downwards is as follows:-

(a) PMM (maximum thickness 500 feet) predominantly unconsolidated sands and thin clays and occasional sandstones.

(b) LMM (maximum thickness, 1400 feet) subdivided into five zones as follows:-

Zone 'a': Unconsolidated sands and sandstones, rare clays. Sandstones grade to sandy carbonates in north-central basin. Sands increase at expense of clays in marginal areas to east, west and south, and the relation is repeated in all other zones.

Zone 'b': Composed predominantly of clay with interbedded carbonates and sandy carbonates in north-central basin and some sands increasing to marginal areas.

Zone 'c': Composed predominantly of sands with some clays changing to sandy carbonates in north-central basin.

Zone 'd': Composed predominantly of clays with subordinate sands in main basin and interbedded with sandy carbonates to north; sands progressively increasing to marginal areas.

Zone 'e': Composed of transitional sandy faces with interbedded clays.

(c) Oligocene: (maximum thickness 1300 feet). Composed predominantly of sand with clays which are either restricted to lower half or more generally dispersed throughout the sequence in the central basin.

7.4 Hydrogeology of the Nubian Aquifer

(i) The main peizometric gradient of the Kufra Basin is directed north-eastwards into the main Nubian Basin which has outlets to the north in various oases and the large sabkhats of Quattara and Siwa. The gradient could be steady-state with discharge to the north balanced by recharge in the Tibesti and Ennedi Highlands to the south and south west; or transient relating to ancestral head levels and subsequent (including current) discharge rates.

In view of the fossil age (25 000-44 000 years) of all samples collected at Kufra and the extremely low rainfall over the main Basin (0.1 inch annual at Kufra in 7 years), significant current recharge over the Nubian outcrop seems unlikely.

(ii) A subsidiary gradient trend northwards may relate in part to discharge in the minor oases in that direction (Bzema, Rebiana) but is more likely a regional feature related to flow patterns within the deeper Nubian (Continental Mesozoic) below the Sirte Basin.

(iii) The apparent trend deduced from the calculated freshwater heads within the Nubian of the southern Sirte Basin is directed to the east and southeast. The combined trends including the subsidiary trend from the Kufra Basin probably continue eastwards north of the Palaeozoic outcrop and into the main Nubian Artesian Basin system as suggested above. The gradient in the Sirte Basin must be transient relating to ancestral head build-ups which could have developed at any period since deposition. Some flushing by fresh water is apparent in the south which seems unlikely to have occurred prior to the Post-Middle Miocene times.

(iv) Water quality in the Nubian Aquifer of the Kufra Basin is extremely good (TDS<500 ppm) at Kufra Oasis and the other smaller oases in the general vicinity, and information from the drilled wells at Kufra shows that quality persists to depth.

(v) Water quality in the deeper Nubian of the Sirte Basin is moderate in the south but deteriorates rapidly to the north becoming highly saline.

7.5 Hydrogeology of the Post-Eocene Aquifer

(i) The piezometric contours in the Upper Post-Eocene of the Southern Sirte Basin which includes the Phase 2 Area strike generally east-west with a gradient to the north towards the main discharge areas in the vicinity and eastwards of the Gulf of

Sirte.

(ii) Data on the Upper Post-Eocene is mainly restricted in Phase 2 to PMM and LMM, Zone 'a' but limited data on Zone 'c' in the central proposed well field area shows a slightly higher head (approximately 1 foot). At T(Q1-65) in the north-west corner, head levels in the deeper LMM and Oligocene are also slightly higher (same order of magnitude) than in the upper levels (here LMM, Zone 'a'). The indications are therefore that there would be small vertical components of flow within the Post-Eocene Aquifer system in the Phase 2.

(iii) Considering more regional head values in the Southern Sirte Basin in relation to structural stratigraphy, there is a general indication of complete hydraulic continuity within the Post-Eocene unlike the separation which develops further north between the LMM and PMM (Phase 1 Area).

(iv) As in the Kufra Basin, the fossil age of the water in the sampled wells (4 samples all showing ages in excess of 45 000 years) in association with the low rainfall, lack of evidence of surface run-off also viewed in the context of the low rainfall and the high moisture deficiency of the surface sands, all indicate the unlikelihood of recharge over the outcrop areas. The bend of the piezometric contours on the far west side of the Basin adjacent to the Haruj Al Aswad may relate to recharge either current or from a relatively recent recharge period and the possibility is strengthened by the evidence of local, surface run-off patterns indicative of possible wadi recharge. Recharge to the Post-Eocene aquifer system in the vicinity of the Tibesti Mountains is possible but seems unlikely to be a significant factor in view of the extreme attenuation of the Post-Eocene into the Tibesti Sarir embayment. Upward and lateral leakage from the Nubian in the southern Phase 2 is a more likely possibility and may account for the distinct bulge of the piezometric contours in that area and the general convergence of head levels towards these in the Nubian Aquifer. The more southerly strike of the contours away from the "bulge", particularly to the east would suggest a general downward gradient with absence of recharge along the Palaeozoic outcrop which borders the Kufra Basin to the north.

(v) The gradient in the Upper Post-Eocene is steep in the south and decreases northwards. The feature is consistent with the variations in transmissibility values calculated to the base of Zone 'c' and relates to the increasing saturated thickness of the more permeable PMM formations. The base of Zone 'c' is regarded as a suitable level with all overlying horizons in effective hydraulic continuity and no localised recharge to the unit other than possibly in the far south. Under these conditions, transmissibility should relate to the gradients.

(vi) Water quality data is mainly available from upper levels of Post-Eocene. Quality is generally fresh (less than 3000 micromho SEC) in the western two thirds of the Phase 2 but the dissolved solids increase significantly on the eastern margins, particularly to the north-east. Main lateral quality changes appear generally independent of lithology and occur along the piezometric strike. A suggested explanation relates the changes to varying recharge periods with fresher water being younger and located along zones of localised recharge, e. g. ancient wadi systems.

(vii) In the central well field area, water quality close to the water table is poorer than at depth. The feature may be related to ancestral evapotranspiration effects developed when the water table was nearer to ground level. On this assumption, the poorer quality water may occur in a relatively thin zone of restricted lateral extent along the axis of the topgraphic low.

(viii) Information on the quality in deeper levels of the LMM and Oligocene is more limited but available data indicates good quality likely to be maintained at depth in the western Phase 2 but may deteriorate in the east. A greater dependence on lithology may occur because of increased restriction to localised flushing. More information should be possible to obtain by detailed log analysis utilising the known variations as standards.

7.6 Hydraulic Parameters

(i) Parameters required are transmissibility and storage factors which will include an artesian storage coefficient and a gravity controlled specific yield.

(ii) Transmissibility is the product of permeability and thickness. Since the final aim of this phase of the study is the production of data for a predictive model extending over the relevant section of the Post-Eocene Aquifer, values are required for some 600-800 feet of saturated aquifer consisting of a variable assemblage of sands, clays and sandy clays and sandstones grading to sandy carbonates.

(iii) In situ determinations of transmissibility in this thick and variable sequence have been carried out by controlled pumping tests on defined limited intervals. This was necessitated by the difficulties of analysis of data from a sequence which includes an upper unconfined section and several subordinate intervals each separated by low permeability clay layers. Total analysis would require a large number of piezometers screened at the various levels, which in the circumstances was impracticable.

The technique adopted has been to select suitable intervals which would respond in controlled fashion (artesian or leaky artesian) with piezometers set in the appropriate responding horizons including levels both above and below the main responding interval in order to assess the degree of independence and the validity of the analytical technique.

(iv) Results of the tests have confirmed a relation evaluated in the Phase 1 study which is that permeability can be determined to a fairly close degree of accuracy in unconsolidated formations by suitable analysis of size variation data.

(v) Cemented formations (calcareous sandstones and sandy carbonates) have been shown by flow velocity logging to have lower permeability from that of the component sand fraction, a feature which is to be expected. An attempt has been made to relate the actual permeability to the grain size permeability by means of a correction factor. Cementation is known to be generally weak and variable but the controlling factors are unknown. Provisionally it has been assumed that grain size could have a significant effect such as, for example, in a banded sequence. Present studies have simply attempted to establish the quantitative relations between the actual permeability and grain size permeability at the few sites analysed in detail but obvious additional lines of approach include log analysis to determine total porosity (neutron, electric logs), proportion of component minerals (crossplots of two porosity logs), and degree of consolidation (sonic transit time). Information from such studies may show whether a valid relation exists, perhaps over a restricted range, between grain size permeability and true permeability in cemented formations or may permit the establishment of other criteria on which permeability can be obtained.

(vi) Extrapolation to determine transmissibility values at sites other than those tested as described above has had to be based on general log analysis weighted in a variety of ways. It was found significant, for example, to differentiate between different levels within the PMM which had considerable different permeabilities but no marked difference in porosity. This feature increases the difficulty of extrapolation from the available data.

(vii) Values of artesian storage coefficients and in some cases vertical permeability of semi-confining layers can be obtained from short term pumping tests. Specific yield can best be determined from the long term tests which are planned. Since the water table occurs mainly within the unconsolidated formations of the PMM, some data on specific yield is available from sampled sites using the graphical correlation discussed in the Phase 1 Final Report.

7.7 Water Resources

(i) Overall resources in both aquifer systems are clearly very large but considerable complications exist in relation to development both by virtue of the remote location and the complexity of the aquifer system. Aquifer resources in consequence are most realistically assessed in terms of well fields designed for a specific purpose i. e. in situ large scale mechanised irrigation or small scale social development schemes; piping to provide water elsewhere. Prediction of drawdown patterns and likely water quality changes for varying well deisgn and well-field arrays are best evaluated in the present circumstances by digital modelling techniques.

(ii) Information on the Nubian in the Phase 2 is very limited and modelling not yet justified. Discussions in this report are mainly limited to aspects of aquifer response, water quality variations and geological structure affecting boundary conditions and interrelations with the Post-Eocene sequence. These considerations mainly refer to proposed developments in the general region of the southern Phase 2.

(iii) The Post-Eocene sequence has been subdivided into an upper unit taken down to the base of Zone 'c' of the LMM and a lower unit to the base of the Oligocene. The subdivision is based partly on practical considerations since the wells in the current scheme are not planned to exceed 1000 feet in total depth and in the location of the proposed field to the north of 26°45'N, this would effectively limit wells to the base of the LMM, Zone 'c'. The subdivision also appears to be related to the fundamental hydrogeological structure with the common boundary occurring above the main clay unit, Zone 'd', of the LMM. The underlying aquifer unit below the main clay, i. e. Zone 'e' and the Oligocene will probably respond for a lengthy period of time in artesian fashion. The upper formations which comprise the LMM Zone 'a' and the PMM will respond in complex fashion but more probably in the relatively short term as leaky artesian. The piezometric map of the upper Post-Eocene refers essentially to this unit and gradients appear to be generally parallel to that of the water table with little vertical component. Leakage from deeper horizons into the upper unit seems unlikely except perhaps locally in the extreme south.

(iv) Preliminary modelling of the steady-state system in the Upper-Eocene of the Phase 2 has been initiated but not yet completed. The values of transmissibility obtained at the five sites along the north-south axis accord with the piezometric gradients but because of the difficulties in extrapolation to unsampled sites, further time is required to manipulate the data in order to obtain adequate accordance of the regional variations in transmissibility with the piezometric surface. This relationship is fundamental to the preparation of the steady-state model.

(v) The unsteady-state model requires the incorporation of additional conditions notably affecting the response of the aquifer and the significance of vertical flow components. This is a matter on which information is completely lacking except by inference and it is hoped that the longer-term pumping tests which are proposed for the initial six production wells will provide some of this essential data. The three tests carried out to date for 5 days duration showed artesian response in the observation wells throughout the duration. The dual piezometers designed for the first six production sites include settings suitable for short-term analysis and also for measurements of the longer-term responses.

(vi) The clay layers in the PMM and Upper LMM in the Phase 2 are not usually thick (generally of the order of 2 - 5m) and if they correspond with the PMM clays in the Phase 1 Area will have relatively high permeability for clay material. That being so, the upper unit would be expected to behave in the relatively short term in leaky artesian fashion although it has differed from the PMM in the Phase 1 in not showing indications of such a response in the 5 days tests. The model studies in the Phase 1 showed that with the values of permeability and thickness assigned to the significant confining clay horizon, the leaky model responded in the fairly short term effectively as water table. A similar situation may prevail in the Phase 2 but it cannot be assumed.

7.8 Well Field Location

(i) The well field proposed by Tipton and Kalmbach on the basis of information available in early 1974 is located in the Calanscio Sarir west of the Sand Sea. The 500 wells are spaced in 2 main and 2 subsidiary lines within a belt 130-140 km and 20-30 km wide, elongated north-south between latitudes $26^{\circ}45'$N and $28^{\circ}00'$N. The selection of the site has been controlled in part by requirements of soil and terrain. From purely hydrogeological considerations there are advantages as well as disadvantages in the choice of location and whether or not alternative or modified sites are possible, it is as well to be aware of any limitations since they might be counteracted to an extent by flexibility in well design, spacing or abstraction rates. Most obvious disadvantages of the site are:-

(a) It is located down the dip of the piezometric gradient.

(b) It occurs in the line of the main axial trough in which clays assume most significant proportions, particularly in the LMM.

(c) Although it is sited in a belt of good quality water, there is deterioration eastwards and particularly so to the north-east. The significance of the latter feature would depend on aquifer response and the speed of progagation of the cone of influence.

The main advantage of the site is that the saturated thickness of the more highly permeable PMM increases towards the axial region, counteracting the increase in clay percentage of the LMM. In general it would seem that the location is not too unfavourable except in the more northern areas where a shift westwards would be desirable both in order to obtain greater distance from the location of poor quality water and from lithological considerations to improve the specific capacity of wells.

7.9 Well Design and Spacing

(i) Well spacing and design is mainly determined by a combination of factors which include transmissibility, specific yield, specific capacity and pumping rate, and total abstraction from the aquifer. Total available drawdown in the wells i.e. combined pumping drawdown and interference drawdowns, must not exceed the limit set by the length of the well casing for a selected period of time, which might be 50 years. Specific capacity relates mainly to the transmissibility of the screened intervals on the assumption that quasi-steady state conditions will develop fairly shortly after pumping starts in consequence of leakage. For the present scheme a design pumping rate is 66 litres/sec.

(ii) Selection of screen and casing lengths is a compromise decision in which improvements in specific capacity may be offset by reduction in total available drawdowns. A quantitative discussion is provided in section 6.2.4.2 of this report. Selection of depths to drill and likely sections to be screened can be obtained from the maps and lithological sections provided with this report. Since interference drawdowns cannot be predicted with any degree of certainty, toleration limits can be set based perhaps on the predictions of the Tipton and Kalmbach model. Casing and screen lengths can be manipulated to give optimum specific capacity within the corresponding limit of total available drawdown. For initial wells in an area, flexibility is desirable and preliminary calculation of various combinations can be made based on inferred transmissibilities from lithological sample analysis. Data for the well tests can be utilised in the design of the subsequent wells. It may prove that because of low specific capacity, spacing should be increased in a particular area in order to keep interference drawdowns within the the tolerance limits. The need to space the preliminary wells until adequate information on aquifer response becomes available is, therefore, emphasised.

7.10 Recommendations

(i) Work should be continued on model preparation incorporating the results of the planned long term tests.

(ii) The first 50 wells should be spaced several times wider than a spacing based on assumed water table response and average specific capacities. Subsequent wells can be drilled in between in such numbers as may be warranted.

(iii) A pilot project is desirable in which detailed measurements of abstraction and drawdown are continued for sufficient time to calibrate the model and to permit prediction of long term effects before the main project is initiated.

(iv) Consideration might be given to modifying the location of the well field, particularly in the northern area.

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