Libyan Arab Republic

Kufra and Sarir Authority

Jalu - Tazerbo Project: Phase 1

FINAL REPORT

by

E P Wright, A C Benfield, W M Edmunds, R Kitching

with

2 APPENDIXES

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Institute of Geological Sciences
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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.

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1. INTRODUCTION AND OUTLINE

The Phase 1 area extends over 40 000 sq km in north-central Cyrenaica and includes several of the major oil fields of the Sirte Basin and the oases of Jalu and Augila. Ground water investigations commenced in May 1971 and the associated test drilling programme in December of the same year. The latter was scheduled for completion in the Phase 1 Area by August/September 1972 but in the event continued until February 1973. Test drilling then commenced in the Phase 2 Area, to the south of Phase 1 and is still continuing (June 1974).

An interim Report was presented in May 1973 and has provided the essential data and main conclusions of the Phase 1 Area studies. The Interim Report should be read prior to the present document which deals in detail with certain specific aspects of the study listed below. The reasons for making these more detailed studies and the general findings are outlined.

1.1. Stratigraphy

Two aquifer systems were recognised in the Phase 1 Area, one within the Post-Middle Miocene (PMM) and a second, multiple system within the older Lower and Middle Miocene (LMM) and Oligocene Formations. The PMM as discussed in the Interim Report included the Calanscio (Upper Sands) Formation and the deeper Aklash Formation. The latter was of significance mainly to the north of latitude 29°. Recent palaeontological study of core specimens from J(C1-95) has shown however, that the Aklash Formation is of Middle Miocene age. It has therefore been necessary to redraw the base of the PMM at the base of the Calanscio Formation and to abandon the use of the term Aklash Formation. Differences to the original base of the PMM (shown in Map Figure 7 of the Interim Report) are not very marked except to the north of latitude 29°. The base of the Calanscio Formation is now regarded as coincidental with that of the PMM and is shown in the sections which accompany this report (Map Figures 1-4) and in a map of the Phase 1 Area (Map Figure 5). The stratigraphic changes do have certain hydrogeological implications which are discussed below.

1.2. Sedimentology

The results of the aquifer pumping tests carried out at the 11 exploration sites in the Phase 1 Area showed that under standard methods of abstraction in high capacity wells and for the short period of the tests (5-10 days), the PMM aquifer behaved generally in leaky artesian fashion. Wells with short screens at the water table showed either considerably lower drawdowns than those screened at the deeper pumping levels, or in some cases no apparent drawdowns at all. This behaviour was attributed to the presence of interbedded clay layers occurring above the screened intervals. Since well drawdowns under leaky artesian conditions will differ from those occurring in a uniform water table aquifer with comparable constants, and these differences could have important consequences upon well field design and long-term performance, a detailed study was carried out of the clay layers in an attempt to evaluate their regional occurrence and extent. It would appear that the Calanscio Formation is essentially composed of a fluviatile sand sequence interbedded with thin clays, individually of limited extent but as lithological units always present. Lateral continuity of any clay bed could be expected to lie in the range 2000 to 20 000 feet. These findings have been used in constructing a stylised mathematical model, incorporating a clay layer at a significant position in the aquifer.

1.3. Correlation of aquifer characteristics based on grain size analyses with those derived from aquifer pump testing.

Data on the aquifer constants for the PMM aquifer were derived from a relatively few pumping tests in scattered localities. The results of these tests appeared sometimes anomalous but the more reliable values were used as an initial basis together with the gradient of the water table for the construction of a steady state model of the PMM aquifer. Since the Calanscio Formation consists largely of unconsolidated sands with clay minerals mainly segregated in discrete lithological units, a correlation of permeability and specific yield with grain size distribution is theoretically feasible. Several advantages are possible if a eliable correlation is available. Aquifer con - tants can be determined in a single well or bore- iole without carrying out pumping tests requiring oth production and observation wells. Alterna-ively, samples can be used as a check on pumping test results which is particularly important n this context since the drawdown plots from vells within a thick heterogeneous sand/clay nterbedded sequence sometimes show anoma-ous or inconsistent results.

The results of the studies have shown a airly good correlation of the permeabilities ased on grain size analysis with those from umping test analyses and in most cases have esolved apparent discrepancies. They have enerally confirmed the regional values used in he model construction. They also emphasise the eed to obtain accurate lithological samples not nly for the purpose of deriving hydraulic con-tants or to confirm data from pumping test an-lyses but also to assist in well completion esign and to indicate an order of efficiency and ence the degree of development of production ells.

. 4. Regional groundwater patterns.

The assimilation of the original Aklash ormation into the Lower and Middle Miocene has equired modification to the map of the piezo-ietric surfaces (Figure 9, Interim Report) and ie revised version is Figure 6 of the Final eport. A more detailed evaluation of the re-ationship between the two aquifer systems is now easible. Head levels in the PMM and LMM quifers are approximately co-incident in the outh-east corner and to the north of 29° 10'. The elations now suggest that depletion of the head ifference which exists along the western PMM oundary may involve more extensive leakage rom the LMM into the PMM than hitherto upposed. The implication has certain conse-uences upon the model analysis which will be iscussed below.

. 5. Hydrogeochemistry.

The Interim Report provided a generalised escription of the hydrochemical patterns in the MM and shallow LMM aquifer systems, includ-ig those of both major and minor element con-entrations, as well as consideration of age ating and of water quality in relation to use. It iould be noted that the term 'quality' refers iroughout this report to chemical and not acteriological quality. The Final Report con-iders all these same aspects but in greater etail. The Total Dissolved Solids (TDS) Map (Figure 10 of the Interim Report) required to be re-evaluated in relation to the later information of the spatial distribution of the two aquifers. In the event, there has not been time to produce a revised version, but the correct relations are exemplified in the Chloride Map, Figure 7, of this Report. To the north of latitude 29° 00' the saturated PMM is considerably reduced in thickness and wedges out at some distance to the east of the PMM outcrop boundary. The marked deterioration of water quality shown in the TDS map therefore refers essentially to the LMM aquifer and not the PMM as originally supposed. At J[C1-95] on latitude 29° 27' where values are available for both aquifers the total mineralisation contents are not greatly different although the LMM is higher in sulphate. Farther north no information on the PMM is available. In any event, the reduced saturated thickness of the PMM also reduces its significance from the viewpoint of available water resources. Quality changes do occur elsewhere in the PMM aquifer, and the detailed studies have confirmed that general deterioration east of Gialo Oil Field exists throughout the saturated thickness and that the changes are likely to be related to internal lithological factors. The further increase in dissolved solids within a restricted zone to the north of Jalu Oasis is attributed tentatively to localised evapotranspiration effects, probably effective over a lengthy time period. The significance of the conclusion is that quality is likely to improve with depth although not below the regional 'background' range. Further north still, a more general deterioration seems probable in consequence of general lithological changes, particularly in the LMM aquifer.

The detailed results of the age determinations and the associated palaeoclimatic data are presented here. A general correlation of age with depth is apparent in the PMM aquifer in this area. Additionally, superimposition of younger water occurs in a subsidiary zone extending from the central freshwater lobe in the south east corner. The zone is relatively narrow but extends deeply into the PMM aquifer, confirming indications of its origin by recharge from a local wadi system. The chemical quality of this younger water is good and although resources are limited in the known areas, tracing the continuation of the zone beyond the boundaries of the Phase 1 Area could have significance in water resources evaluation. The existence of other such zones of very good quality water in central Cyrenaica is clearly a possibility.

1. 6. Water resources

1. 6. 1. Miocene/Oligocene aquifer systems. The preparation of a number of detailed geological cross-sections in the Phase 1 Area has allowed a more informative but still qualitative appraisal of the potential of these aquifers. From the viewpoint of water quality and aquifer lithology, the most favourable locations are in the southern Phase 1 Area. Quality is fair to good at shallow levels over much of the area west of the PMM boundary and south of latitude 29° but lithological considerations indicate probable deterioration with depth. It must however be emphasized that information is severely limited and proper evaluation would require detailed test drilling.

1. 6. 2. PMM aquifer - The resources of the PMM aquifer have been evaluated by construction of digital models and the imposition of practical abstraction schemes. The steady-state condition assumed inflows and outflows based upon estimated transmissibilities and the piezometric gradients at the northern and southern boundaries respectively. Some leakage from the LMM was required for final equilibrium adjustment, mainly in the boundary zone in the south-west Phase 1 Area (see Map Figure 5C in the Interim Report). Some readjustment of the boundary flows may be required in consequence of the stratigraphic changes referred to above, and the possible significance of these re-adjustments are considered. Additionally, the revised piezometric map indicates that leakage from the LMM to the PMM may cover over a more extensive area than hitherto supposed. Such leakage would increase with development of the latter aquifer in consequence of increasing head differentials. Whether the effects of these implied boundary changes in the PMM aquifer have significance for the schemes previously studied is a matter for consideration in this Report. For the Interim Report abstraction schemes, it was assumed that the PMM aquifer would behave as a homogeneous unconfined body with a specific yield of 0. 1. (10%). For reasons relating to water quality and available drawdown, proposed well fields have been limited to the central Phase 1 Area where saturated thickness exceeds 80 metres and the dissolved solids content is less than 2000 mg/1. Brief details of schemes studied in the Interim Report are as follows:-

1. Scheme A: 328 000 m^3/day from 8 groups of 6 wells distributed in two localised areas with centres at 18 km distance. This simulation of a high density well field showed predicted pumping drawdowns reaching design screen levels within 10 years.

2. Scheme B: 152 000 m^3/day from 33 wells spaced in three equal rows 12 km apart with individual well spacing of 4 km. The predicted simulation showed that pumping drawdowns were unlikely to reach design screen levels within 50 years. The design abstraction was equivalent to the proposed requirement for the Agedabia water supply.

The schemes modelled in the Interim Report assume relatively favourable conditions of aquifer behaviour. Specific yield could however exceed 10% and upward leakage from a deeper aquifer could further reduce drawdowns. Upward leakage would be disadvantageous if the leakage was of poor quality water. Increased drawdowns could also occur due to vertical components of flow in relation to lower vertical permeabilities than design values. A particular case in point relates to the presence of interbedded clay layers. These occur throughout the PMM sequence although individual layers may be of limited extent. The complexity of the configuration is likely to have precluded modelling a realistic configuration, even if sufficient information had been available, but a stylised situation has been modelled and applied to Scheme B. A clay layer 3m thick is assumed to occur within the upper levels of the PMM, i. e. above the production well screen, and to extend across the main area of the proposed well field. The design thickness is consistent with known values and the situation modelled is regarded as being equivalent to overlapping layers of more limited extent. Vertical permeabilities of 0. 001 and 0. 007 m/day were assigned to the clay layer, the figures being based upon analysis of leaky artesian plots from the Phase 1 test sites. The results of the modelling indicate that under these assumed conditions, the long-term drawdowns will be essentially identical to those resulting from simple unconfined conditions. Possible aspects which could modify these conclusions are considered, the most probable being lower values of vertical permeability of the clay horizon.

The second scheme modelled and discussed in the Final Report is a well field design proposed by Messrs Tipton and Kalmbach of Denver, U. S. A. The field is located centrally in the Phase 1 Area, approximately co-incidental with that of the IGS Scheme B, and consists of three rows of wells converging northwards to a point from which an aqueduct extends to a proposed irrigation area (7000/10 000 hectares) to the south of Augila. The predicted drawdowns based on the IGS Scheme B boundary assumptions are seen to be locally excessive and requiring increased well spacing and/or reduced abstraction rates to permit long term usage.

1. 7. Development, research aspects and recommendations.

At the present time, abstraction of ground water in the Phase 1 Area is of small magnitude from wells in the Jalu and Augila Oases and at the oil camps of Nafoora, Amal, Occidental, Pan-American, Gialo (Oasis) and Aquitaine. Water is required for irrigation and domestic use at the oases and for both industrial and domestic use at the oil camps. The former includes supplies for water drive in the oil reservoirs, and abstractions are from the PMM as well as from the deeper Oligocene and Miocene aquifers.

An overall plan for the Phase 1 Area development does not appear to be in existence. Supplies for local irrigation and for coastal town supplies have been given general consideration (IGS Schemes A and B). The well field designed by Tipton and Kalmbach to provide water for irrigation areas to the south of Augila is another specific proposal. The location for use is based on soil considerations and the proximity to existing oases. With some reservations on well spacing and abstraction rates and with reasonable care in calibrating the predictive model over a phased development period, it would seem probable that the required supply of good quality water for a lengthy period is assured. On the limiting condition of water quality, the well field requires to be located in the central Phase 1 Area. But water of poorer quality with dissolved solids in the range 2000/4000 mg/1, can also be adequate for irrigation of the more salt tolerant crops. Although the crops to be grown are not known, it is evident that if water of poorer quality can be used, development sites closer to the area of use would be possible. One possible suggestion is to commence with in-situ irrigation, eventually bringing in piped supplies from the central Phase 1 Area, as and when required. The availability of water in the area between Augila and Jalu has not been evaluated fully but there are indications that supplies at depth will be better than the near surface supplies. This condition would require confirmation by test drilling.

The above discussion refers to a specific project in which alternative or integrated proposals are suggested. In considering overall future development of groundwater in the Phase 1 Area various aspects should be mentioned. The significance of such aspects will vary according to the planned development. These aspects will be stated without further comment.

(1) Piped water to coastal areas - On the assumption that a minimum requirement is a dissolved solids content of less than 2000 mg/1, supplies can be obtained in the Phase 1 Areas from the PMM or LMM aquifers. Other factors to be considered are distance to the coast and general availability, i. e. the practical response to well field development. Assured supplies of moderate volumes can clearly be provided by the PMM aquifer in the central Phase 1 Area (IGS Scheme B). There is the added convenience of nearness to sources of power. If the PMM is to be considered for both coastal supplies and irrigation, an assignment of priority must be made since supplies are limited. Abstraction for coastal supply from the LMM could be considered since quality may be within the required limit quoted and distance to the coast of comparable order. Information on the LMM is more limited and there are certain other disadvantages. Comparable conditions to those in the PMM with an extensive thickness of saturated sands, do not occur until the southern Phase 1 Area is reached. A possibility which might be considered would involve exploratory drilling followed by a phased development commencing with abstraction as far north as convenient and bringing in supplies from farther south as and when required. Ample supplies are likely to be available in the far south, should it be necessary to extend there eventually.

(2) Irrigation - Factors include the presence of good soils, the availability of water either locally or by piping, and social-economic aspects. The current project has taken all these factors into account but a suggestion is made here to consider the use of nearer supplies of poorer quality water. If the proposal is acceptable, further test drilling in the eastern Phase 1 Area will be necessary in order to ascertain the extent and availability of water within certain defined limits. Well field developments and associated predictive models would need to be more carefully controlled and calibrated on account of the higher water salinity. However, once again it may be feasible to operate a phased development bringing in piped supplies over longer distances as and when required. The proposal could have distinct economic and other advantages.

(3) The use of good quality water for industrial use e. g. water drive injection in oilfields, would seem to be unjustified since more saline water is readily available at depth. There are of course short-term economic considerations for such practices.

(4) All future development should be controlled and monitored to provide as much information as possible. Examples of this procedure include the proper collection of geological and hydrological data from all wells drilled for whatever purpose. The need to drill suitable observation/exploration wells, whether for general information, or to assist the calibration of predictive models must be recognised, as must the advantages of phased development.

2. HYDROGEOLOGY OF THE PHASE 1 AREA

2.1. Geology

A general discussion of the geological setting and history of the Phase 1 Area and a detailed account of the stratigraphy and lithology of the Post-Eocene formations were given in Section 2.4 of the Interim Report (1973). This information will not be repeated here as the main purpose of this section of the Final Report is to present further data that have been acquired since the preparation of the Interim Report and to discuss the changes in the definition of the stratigraphic succession that these have necessitated. Cross-sections showing the lithological and stratigraphic variation of the Post-Eocene sediments across the Phase 1 Area have been prepared and will be referred to in the following discussion of the various stratigraphic units.

New data have been obtained on four aspects of the geology of the Phase 1 Area - the palaeontological dating of core sediments from J (C1-95), a series of grain size frequency distribution parameters on samples of the Calanscio Formation from Project boreholes, data on the ocurrence and lateral extent of clay beds within the Calanscio Formation and lithological data on the Oligocene and Miocene successions abstracted from oil company well logs. The most important change resulting from the acquisition of these data is major revision of the Post-Middle Miocene sequence as previously defined, including the abandonment of the term Aklash Formation. Other developments include the establishment of confirmatory evidence for the fluvial nature of the depositional environment of the Calanscio Formation, the main aquifer of the Phase 1 Area, and a fuller assessment of lithological variation in the Oligocene and Miocene sediments as illustrated in the cross-sections.

In addition, a subsection is included at the end of this section of the Final Report in which the presence of a deep fossil drainage system and associated channel-fill (Barr and Walker, 1972; Walker, B.R., personal communication, 1974) in the region of the north and north-east boundaries of the Phase 1 Area is discussed.

2.1.1. Revised Stratigraphy of the Post-Eocene Formations

The revised stratigraphic subdivisions of the Post-Eocene formations adopted for the Final Report are given in Table 1, and in the cross-sections A-A', B-B', C-C', D-D' (Map Figures 1-4), the lines of which are shown on the Map Figure 5. It should be noted that the cross-sections have in fact been taken to the base of the Upper Eocene as the very thick limestones of the Middle Eocene Gialo Limestone could be more readily identified in well logs than the more variable Upper Eocene Augila Formation. Subsequent study of the cross-sections has shown, that despite the lithological variability, the top of the Augila Formation can be correlated over the whole Phase 1 Area and this boundary is shown on the cross-sections. Other than in this context, the Eocene formations have not been considered in this Report.

2.1.1.1. Revision of base and subdivision of the Post-Middle Miocene

Micropalaeontological analyses made by the Palaeontological Department, IGS, of core samples from Project borehole J (C1-95) have shown that sandy limestones from two horizons within the Aklash Formation as defined in the Interim Report (Appendix 9) at depths of around 370 feet and 570 feet below ground level respectively contain foraminifera diagnostic of the Middle Miocene (Hughes 1974).

These results imply that the Aklash Formation (or Lower Unit of earlier terminology) lies within the Lower and Middle Miocene Marada Formation and consequently the use of the term Aklash Formation must be abandoned. It may be recalled that in the northern part of the Phase 1 Area where the "Aklash Formation" is thickest, considerable use was made of the sonic log characteristics in distinguishing between the rather similar sediments of that formation and the underlying Marada Formation (Benfield 1972; Interim Report, page 25). It now seems likely that the intermediate degree of cementation indicated by the sonic log reflects deep weathering effects within the Marada Formation rather than the presence of a separate stratigraphic unit.

Such deep weathering and leaching most probably took place in late Miocene times when it is likely that the level of the Mediterrean dropped to at least 1300 feet and probably more than 2000 feet below its present level (Hsu, Ryan and Cita

1973). In response to a lowering of sea level of this magnitude groundwater levels in the Marada Formation would fall markedly and leaching of the predominantly carbonate sediments could take place through a thick unsaturated zone. This in turn could result in the decrease in cementation and increase in porosity indicated by the sonic logs.

Further south where the "Aklash Formation" is thin (generally less than 20 feet) and comprises mainly clayey sands, as evidenced by intermediate values on gamma logs, re-assessment of oil company well logs has shown that in many cases a single lower boundary can be drawn to the Post-Middle Miocene, at which the unconsolidated sands of the Calanscio Formation lie directly on the Lower and Middle Miocene Marada Formation. Such a situation was, of course, always considered to be the case over much of Concession 103 (Benfield 1972). Where a thin unit of clayey sand occurs at the top of the Marada Formation, shallow weathering effects and possible palaeo-soil horizons may provide an explanation.

In other cases where the uppermost bed of the Marada Formation is a true clay, it seems likely that this horizon provided a local barrier to the erosional processes which prevailed before the deposition of the Calanscio Formation.

Following the recognition that the "Aklash Formation" could not be considered as a valid stratigraphic subdivision, the abstracted data of all wells in the Phase 1 Area, together with those well logs available in London, have been re-assessed on the basis of there being a single lithostratigraphic unit, the Calanscio Formation, comprising the whole of the Post-Middle Miocene. In most cases the base of the Calanscio Formation (or Upper Sands of earlier usage) has not been changed from that defined earlier (cf. Benfield 1972), but in certain wells modifications have been made to include slightly lower strata. A map showing the revised base of the Post-Middle Miocene, now coincident with the base of the Calanscio Formation, has been drawn (Map Figure 5) and it should be noted that this map replaces Map Figure 7 of the Interim Report.

2. 1. 2. Oligocene

The abstraction of further data from oil company records, leading to the plotting of the cross-sections (Map-Figures 1-4), has permitted a fuller appraisal of thickness and lithological variations in the Oligocene. The base of the Oligocene, taken at the top of the Augila Formation, had been defined in about 75 percent of the oil company logs and there was little difficulty in correlating this horizon across the entire length of the cross sections. However the top of the Oligocene had been picked in only about half the oil company logs, and in some of these the correlation was clearly in error. Consequently it was necessary to use the cross-sections as a basis for correlation studies. Oasis Oil Company records in the general vicinity of Gialo Field in Concession 59 were taken as the starting point, as in these the top of the Oligocene had been picked in accordance with the formal definition of this horizon given by Barr and Weegar (1972) for Oasis Well E3-59 located within the Gialo Field. Correlations were extended from this area on the basis of agreement with Barr and Weegar's (1972) definition, whilst where the boundary had been picked in other companies logs, this horizon was also utilised if possible.

The cross sections show that the thickness of the Oligocene as a whole is least in the south east of the Phase 1 Area where values of around 800 feet are common. The Oligocene thickens towards the north west and maximum thicknesses of from 1500 to 2300 feet occur in a northwest trending trough, the axis of which extends from south-western Concession 103 to northern Concession 6.

Within the Oligocene, the boundary between the Arida and Diba Formations of Barr and Weegar (1972) has not been identified partly because of lack of time and partly because both units as defined have a marine aspect. Instead, the Oligocene has been divided between a non-marine facies, comprising generally coarse, glauconite-free sands with occasional clay interbeds, and a marine facies consisting of a mixed sequence of glauconitic and calcareous sands, generally fine to medium in grade, shales, sometimes with anhydrite, limestones and dolomites. This method of subdivision is considered to be more meaningful from a hydrogeological standpoint as permeability and groundwater quality are both likely to be appreciably better in the non-marine facies than in the marine facies.

The distribution of the two facies is depicted on the cross sections (Map Figures 1-4) and from them, it is clear that the non-marine facies forms a significant proportion of the Oligocene in the south western half of the Phase 1 Area. In this area, for example in Concessions 123, 126, and LP 2C, the thickness of the facies ranges between 700 feet and 1300 feet (Cross Section B-B'). The facies thins and ultimately dies out both to the north east (Cross-Sections

A-A', B-B', C-C') and to the north (Cross-Sections A-A', D-D') where the marine facies occupies the whole of the Oligocene interval.

2. 1. 3. Lower and Middle Miocene

New data allow the amplification of a number of points made in the Interim Report (p. 22) under this heading. The delineation of the basal boundary of the Lower and Middle Miocene Marada Formation given in the cross-sections(Map Figures 1-4) in turn yields information on the regional variation in thickness of the Formation. It is now clear that it is thinnest in the outcrop area in the southwest corner of the Phase 1 Area where thicknesses range from 400 feet to 700 feet. The Formation is, like the Oligocene, thickest in a north-westerly plunging trough trending from southern Concession 103 to northern Concession 6 in which the thickness ranges from around 1800 feet in the former to around 2900 feet in the latter locations.

The definition of the basal boundary has, however, provided no evidence of the presence of an unconformity at this horizon, such as was described by Selley (1968) from the outcrop section in the vicinity of Reguba (latitude 29°00'N, longitude 19°00'E) to the west of the Phase 1 Area. It is however to be expected that unconformities would be developed preferentially on the edge of the sedimentary basin while sedimentation continued without a break in the centre.

The lithological variability of the Marada Formation is clearly illustrated on the cross-sections. The development of sands and sandstones, probably of fluvial origin and constituting a potential aquifer, in the south west of the Phase 1 Area, and the contrast with the predominantly marine character of the Formation elsewhere are particularly well shown.

With regard to the question of the differing well log characteristics of the Marada Formation and the overlying Calanscio Formation, the absence of an intervening "Aklash Formation" makes the comments made in the Interim Report (p. 23) regarding the contrasts between the two Formations particularly relevant. The re-assessment of well logs carried out in preparation for this Final Report has shown that in both resistivity and sonic logs, sufficient evidence can be discerned for the drawing of a single boundary line between the two Formations.

Finally it can be noted that the micro-palaeontological determinations of the foraminifera from the J(C1-95) core samples (Hughes, 1974) and in particular the discovery of the Alveolinid Borelis melo confirm the Middle Miocene age of the uppermost part of the Marada Formation. This is in agreement with the few palaeontological determinations made by the oil companies in this part of the sequence.

2. 1. 3. 1. Areal lithological variation within the Upper 500 feet (152 m) of the Marada Formation

The revision of the base of the Post-Middle Miocene brings the bulk of the sediments formerly referred to as the "Aklash Formation" within the arbitarily defined unit comprising the Upper 500 feet of the Marada Formation to which the lithofacies analysis studies reported upon in the Interim Report were applied. However, the effect of this change on the sedimentary patterns revealed by the lithofacies studies is relatively small, as over much of the Phase 1 Area the "Aklash Formation" is less than 50 feet thick. Only in the north, and in the east and south east are these values exceeded.

To the north of latitude 29°N, where the thickness of the "Aklash Formation" ranged from around 150 feet to 515 feet in northern Concession 95, much of the strata are limestones, sandy limestones, dolomites and clays, and their inclusion does not affect the lithofacies patterns given in the Interim Report. Only the presence of calcareous sandstones, which may reach 190 feet in thickness, modifies the sandstone isolith pattern given in Figure 1C of the Interim Report. Clearly the "spotty" development of sands and sandstones recognised in the north west to south-east trending belt crossing the centre of the Phase 1 Area extends further to the north east than given in Map Figure 1 C of the earlier report.

In the east of the Phase 1 Area the inclusion of a clayey facies of the "Aklash Formation" increases the proportion of this lithofacies as given on Map Figure 3C, while in the south - east, values for sands are increased, but by only around 60 feet (20 m), which is within the range of values for the central belt referred to above.

Finally it should be noted that the changes discussed above do not affect the general pattern of north-west to south-east trending facies belts referred to in the Interim Report (p. 24). Moreover, the new data on the Oligocene indicate that a similar pattern existed in that period. Its continued existence in Miocene times provides further evidence for there being no significant break in sedimentation between these periods in the Phase 1 Area.

2.1.4. Post-Middle Miocene

2.1.4.1. Designation of the type section of the Calanscio Formation

In accordance with the intention given in the Interim Report (p. 22) and to conform with stratigraphic practice, a type section for the Calanscio Formation has been designated. The section chosen is that between ground level (377 feet above sea level) and 247 feet below sea level in Occidental Exploration Well S1-103 situated at latitude 20° 59'59" east, longitude 28° 45'16" north in the south east of Concession 103. Project Site JA was located at this site (cf Interim Report Appendix 1). A diagram showing the form of the various well logs of the Calanscio Formation interval in this borehole has been prepared (Figure 1).

It may be noted that in some oil company borehole logs in the Phase 1 Area the unconsolidated sands defined here as the Calanscio Formation have been correlated with the Garet Uedda Formation described by di Cesare et al (1963) from outcrops in the north of Concession 82 between 100 and 200 Km northeast of the Phase 1 Area. However, at the type section, Garet Uedda (latititude 29° 40' 18" N, longitude 23°30'23"E) the sequence comprises some 84 feet of quartzitic eolian sands with interbedded sandy shales, locally gypsiferous, which, in the upper 30 feet of the succession, contain a brackish-water fauna of pelecypods, gasteropods, forams and ostracods, and which are considered by di Cesare et al (1963) to be sebkha deposits. While these authors state that in the south of Concession 82, the Garet Uedda Formation increases in thickness to around 160 feet and changes in facies to a more fluvial sequence, they provide no documentation of these changes.

In view of the marked differences in depositional facies and stratigraphic thickness between the sediments of the type section of the Garet Uedda and those of the Post-Middle Miocene in the Phase 1 Area, and because of the lack of detailed correlations both within Concession 82 and between Concession 82 and the Phase 1 Area, it was considered advisable to erect a clearly defined stratigraphic unit, the Calanscio Formation, for the PMM of the Phase 1 Area rather than use the term Garet Uedda Formation. Nevertheless the possibility remains that the fluvial facies of the Garet Uedda Formation is a lateral correlative of the Calanscio Formation and should further studies be undertaken in the area east and northeast of the Phase 1 Area, attention should be paid to investigating these stratigraphic relationships.

2.1.4.2. Distribution and configuration of the base of the Calanscio Formation.

The extent of the outcrop of the Calanscio Formation is shown on Map Figure 5. It may be noted that the boundary defining the western limit to the Calanscio Formation outcrop has not been changed from that given for the Post-Middle Miocene on the map (Map Figure 7) issued with the Interim Report. This boundary was established following a detailed appraisal of oil company photogeological and photogeomorphological map compilations, which showed a clear distinction in surface topography between the rock outcrops and dendritic drainage patterns of the Lower and Middle Miocene and the featureless ground of the Post-Middle Miocene. The fact that there appeared to be evidence only for one surface boundary to the Post-Middle Miocene outcrop, rather than two corresponding to the Calanscio and Aklash Formations respectively, was considered to result from the thinness of the Aklash Formation (less than 20 feet) and from the general similarity in lithology to the Calanscio Formation in the region of the boundary. This difficulty is now resolved with adoption of a single unit, the Calanscio Formation, to comprise the Post-Middle Miocene.

The configuration of the base of the Calanscio Formation (Map Figure 5) shows marked changes in elevation across the Phase 1 Area. The base is highest in the south west and falls to the north east into a depression, the edge of which rises to the north around the Nafoora and Rakb oilfields. A closed basin centred on Concession 103 occupies the north west limb of this depression and is separated by a saddle of higher elevation from a northwards deepening trough located in Concession 95. It should be noted that though the pattern is broadly similar to that shown from the base of the Post-Middle Miocene as defined in the Interim Report (Map Figure 7), differences in actual elevation, and therefore of effective aquifer thickness, exist between the two interpretations. These are greatest in the north where the base of the Calanscio Formation is as much as 450 feet higher than the levels previously given for the base of the Post-Middle Miocene.

2.1.4.3. Grain size frequency distribution data

Since the preparation of the Interim Report, statistical parameters describing the principal characteristics of the grain size frequency distribution have been calculated for

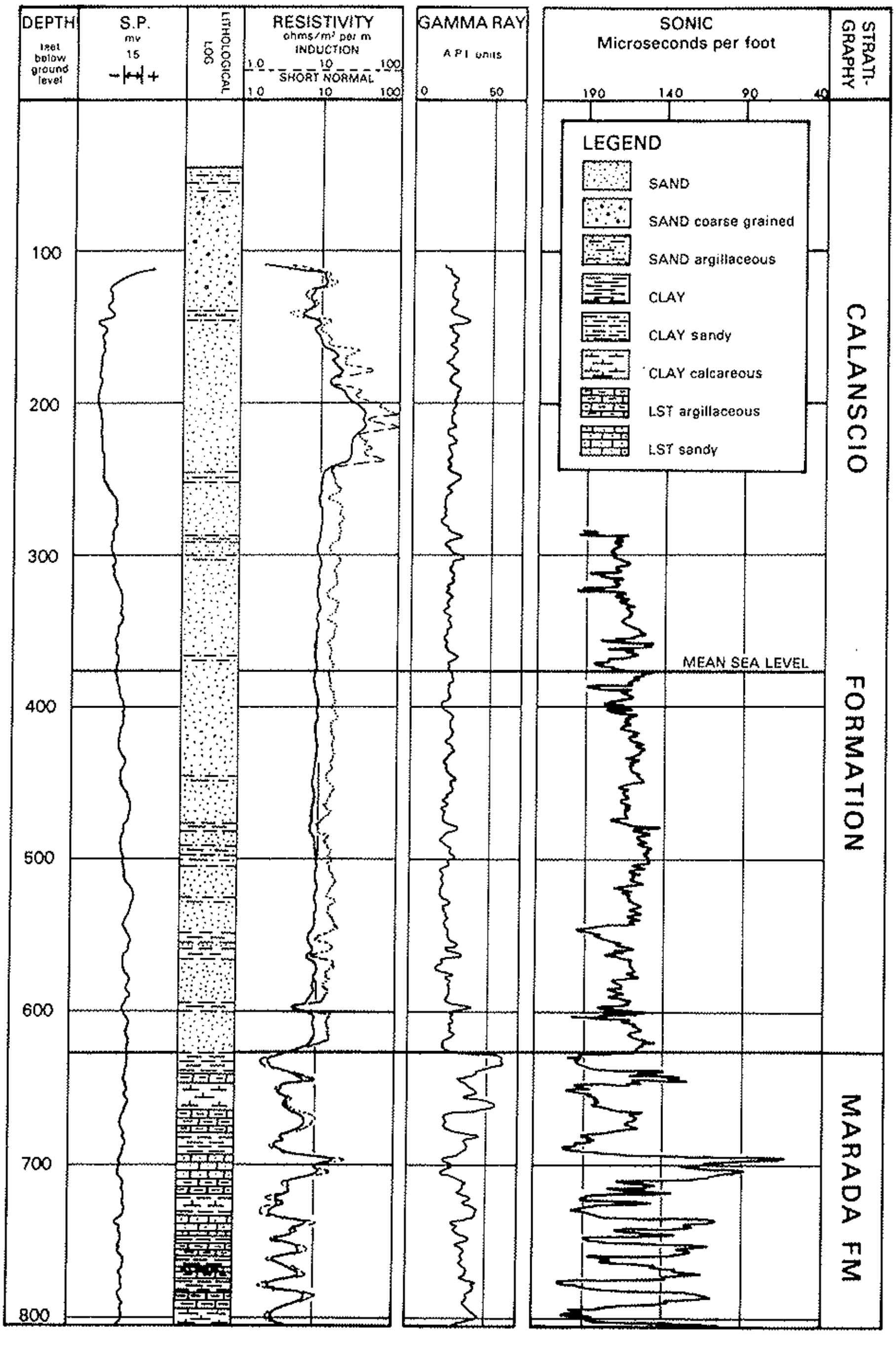


Figure 1. Logs of the type section of the Calanscio Formation in Occidental exploration well S1-103 (Site JA)

every sample of the Calanscio Formation taken during the drilling of one sampled borehole at eight of the eleven Project Sites. The statistical parameters chosen were:

Graphic Mean (Mz) $= \dfrac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$

Inclusive Graphic Standard deviation ( ) $= \dfrac{\phi_{84} - \phi_{16}}{4} + \dfrac{\phi_{95} - \phi_5}{6.6}$

Inclusive Graphic Skewness (Sk_I) $= \dfrac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} +$

$$\frac{\phi_5 + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)}$$

Where ϕ_5 ϕ_{16} etc., are the grain sizes in phi units ($-\log_2$ of grain size in mm) corresponding to the 5th, 16th etc., percentiles on the cumulative curve of the grain size distribution. The parameters were calculated using the IBM 1130 computer of the Computer Unit, I. G. S. for which programs were written by Dr. R. Kitching and Mr J. C. Cubbitt of I. G. S.

A series of cross-plots of mean against standard deviation, skewness against mean, and skewness against standard deviation were also prepared on the computer. The samples from each Project borehole were plotted together and compared with the cross-plots of the same pairs of parameters calculated for samples from a range of known depositional environments (Moiola and Weiser, 1968).

Taking first the cross-plots of skewness against mean, comparison with those of Moiola and Weiser (1968, Figures 3 and 4) which distinguish beach and coastal dune sediments from inland dune sediments, indicate that the Calanscio Formation samples all fall into the former category. However, when the cross-plots of skewness against standard deviation are compared with Moiola and Weiser's (op. cit) Figure 7D, which divides beach sediments from river sediments, then all the samples of the Calanscio Formation are seen to lie well within the fluviatile sector of the graph. Similarly, comparison of the cross-plots of mean against standard deviation with Moiola and Weiser's (op. cit) Figure 7C which also distinguished between beach and river sediments shows that the Calanscio Formation samples without exception are grouped into the river sediment category.

Thus to summarise, the textural parameters of the Calanscio Formation provide evidence that the Formation was most likely to have been deposited under fluviatile conditions. This is, therefore, in agreement with the conclusion based on the evidence of general lithology and lack of fauna given in the Interim Report that the Calanscio Formation represents alluvial plain sedimentation.

2. 1. 4. 4. Data on clay beds within the Calanscio Formation

The significance of interbedded clays in aquifer response required that a detailed evaluation of their occurrence should be made. During the field investigations gamma ray logs were run in existing wells and Project boreholes using an IGS'Portalogger' in order to delimit these clay beds more closely. Some results of these studies were given in the Interim Report and Appendices. Subsequently a more detailed assessment of the gamma ray log results has been made. As this is documented fully elsewhere (Benfield 1974), only the main geological conclusions are given here, while the hydrogeological implications are discussed in the appropriate section below.

The results obtained from the three sites (JB, JC, and JE) at which more than one borehole was logged showed that the clay beds had a limited continuity. At no site could all the clay beds, generally between 5 and 8 in number, be correlated between adjacent boreholes which were located as little as 200 feet apart in some cases. The thickness of individual clay beds varied across the sites, as did their clay contents and their relative positions. Thus they delimited intervening sand beds which could be distinctly wedge-shaped. Splitting of clay beds appeared to occur and could result in the development of lenticular sand beds.

Sedimentologically, the results combine to present a picture of a thick sand sequence split by relatively thin clays, mean thicknesses ranging between 4. 6 ft (1. 4m) and 9. 3 ft (2. 8m), which are individually of limited extent but as lithological units always present. The clays may become sandy and die out laterally or may be cut out by erosion at the lower surfaces of overlying sand horizons. Such a sequence corresponds well with that recognised in fluviatile sediments and thus corroborates the evidence from the grain size parameters regarding the nature of the depositional environment of the Calanscio Formation.

The data from the multi-well sites together with the environmental interpretation, preclude the possibility of correlating individual clay beds from site to site. Thus there is no direct evidence for the lateral extent of individual clay beds, a matter of considerable hydrogeological significance. However in fluviatile sediments such clays are notably impersistent and a ressonable estimate of their extent in the Calanscio Formation is within the range 2000 to 20 000 feet. Evidence from at least one geological sequence considered to be deposited under similar conditions - the Old Red Sandstone of Shropshire, England (Allen, 1962) - is in agreement with this range.

As it was not possible to correlate individual clay beds across the region around Concession 103 with any degree of reliability, a more general approach was adapted to investigations of their areal development. Statistical measures of the frequency and thickness of the clay beds were calculated and their regional distribution plotted. From the map showing the values for the mean number of clay beds per 100 feet of section logged, (Benfield 1974, Fig. 15), it was obvious that clay beds were least common in around the centre of Concession 103 and became more frequent outwards. Mean clay bed thickness was least in a closed area only slightly further to the west (Benfield op. cit., Fig. 16). Finally the percentage of section occupied by clay beds was lowest around to the west of central Concession 103 between F1-103 and B1-108 and values increased in all directions away from this area (Benfield, op. cit, Fig. 17). Thus to summarise, clay beds are least important in the area between central Concession 103 and northern Concession 108.

2. 1. 4. 5. Relationship between Calanscio Formation and Sahabi channel sediments

As a result of an extensive programme of geophysical surveying and associated borehole drilling in the region immediately north and northeast of the Phase 1 Area, Barr and Walker (1972) were able to recognise the existence of a deep fossil drainage system which they named the Sahabi channel (c.f. Figure 2). They postulated that this was cut during an abrupt drop in Mediterrean sea level of least 1300 feet and possibly 2000 feet in late Miocene times for which supporting evidence was provided by the discovery during the Joides Deep Sea Drilling Project of late Miocene shallow water evaporites on the floor of the Mediterrean. They considered that the channel system was filled during the early Pliocene when the sea level returned to a level about the same or a little below its previous position as indicated by the presence of marine Pliocene deposits landward of the head of the Gulf of Sirte.

In the region described by Barr and Walker (1972), the main channel varies in width from less than one kilometer to more than five kilometers, is steep-sided and has a maximum depth, calculated from seismic surveys, of more than 1300 feet. The channel cuts through limestones and dolomites of proven Middle Miocene age which outcrop over much of this region.

The sediments filling the channel are unconsolidated quartz sands and soft, non-calcareous clays in equal proportions. The sands vary in grain-size from very coarse to fine and in sorting, but, according to Barr and Walker, moderate to well sorted sands in the fine to medium range predominate. The sediments are unfossiliferous, apart from rare reworked Middle Miocene forams, and their characteristics suggest deposition under non-marine fluvial conditions.

In their publication, Barr and Walker (op. cit., Fig1) depicted the channel extending upstream from a location within Concession 95 and just beyond the northern boundary of the Phase 1 area, eastwards for some 50 km to a point of bifurcation. From here a tributary continues eastwards for a further 45 km while the main channel runs south eastwards and is proven for some 50 km. Beyond this the main channel is less well defined but Barr and Walker believe it can be traced for at least a further 50 km to the south east. Its course passes through Concession 96, and then Concession 51, where it enters the Phase 1 area, and it can be followed to a point in the vicinity of Gatmir in Concession 102 (Figure 2).

No evidence of the presence of the channel in this part of the Phase 1 area was revealed by the present investigations. However in view of the narrowness of the feature (only around 1 km in this region) in comparison with the 10 km average spacing of the boreholes used for the stratigraphic studies, this is not surprising. Further extension to the south east, which Barr and Walker (op. cit. p. 1244) consider quite possible, would take the channel beyond the eastern boundary of the Phase 1 area.

Following more recent geophysical reconnaissance investigations (B. R. Walker, personal communication, 1974) the Sahabi channel has now been traced further downstream. In

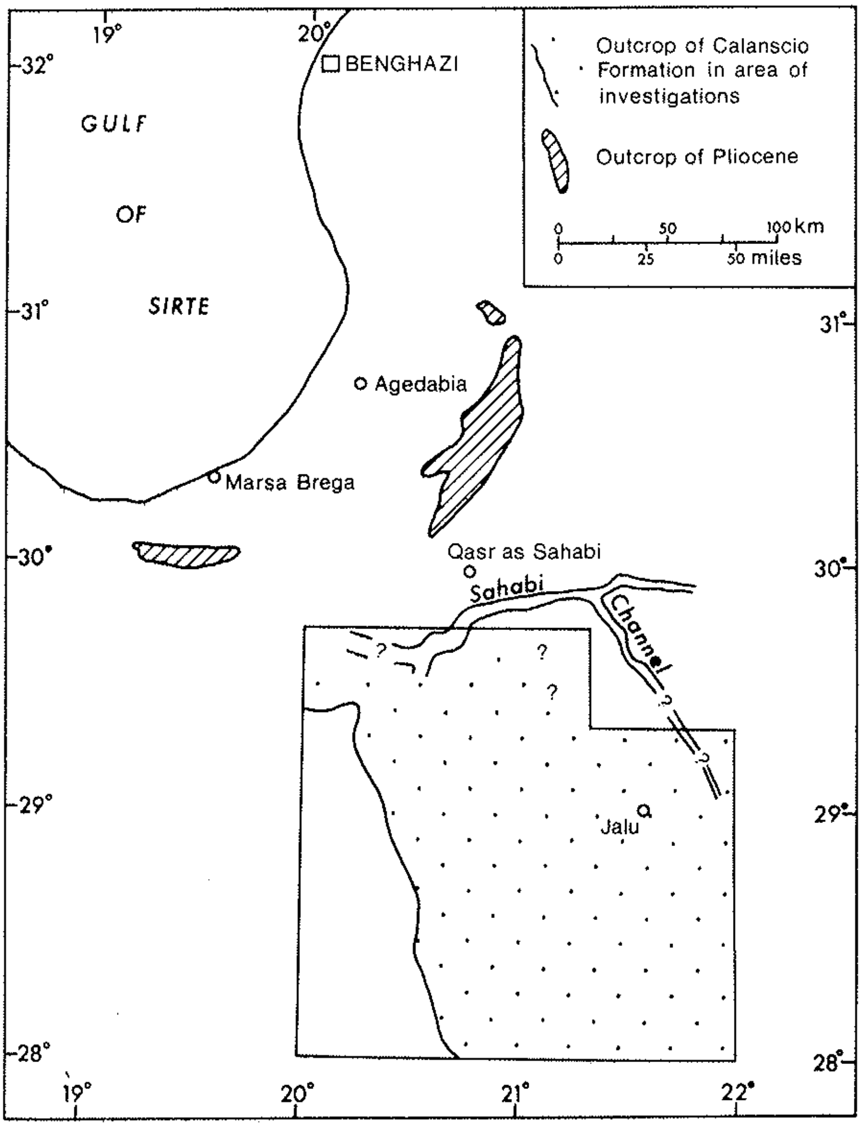


Figure 2. North-central Libya showing the Sahabi channel (after Barr and Walker, 1972, and Walker B R, personal communication 1974) in relation to Phase 1 Area

Concession 95 it first runs south to cross the northern boundary of the Phase 1 area some 18 km north of K1-95 and then turns southwest to the western boundary of Concession 95 where it is joined by a poorly defined tributary from the south. In this segment the channel increases in width to around 9 km and calculations from seismic data indicate maximum depths along the channel axis of from 1300 feet to 1600 feet. Amoco exploration oil well J1-95 lies within the channel but close to its northern boundary. The sediments of the upper 500 feet were unfortunately not logged lithologically but appear from electric, gamma and sonic logs to comprise sands from surface to 63 ft below ground level (14 feet below sea level), sands, clayey in part, with interbedded clays to 193 ft b. g. l. (144 ft b.s.l.), clay, poorly consolidated, to 288 ft. b. g. l. and sands, sometimes clayey to 368 ft b.g.l., resting on interbedded limestones and shales continuous with the fossiliferous Miocene rocks sampled below 500 ft b. g. l. The character of the post Miocene sediments below 193 ft b. g. l. indicates that the channel fill is perhaps more clayey than further upstream. Above this depth, the dominantly sandy nature of the sediments suggests a possible correlation with the Calanscio Formation, though the sequence could also correspond to a more sandy part of the channel fill.

From Concession 95, the channel extends west-north-west through a part of Concession 119 into Concession LP3C. In this Concession, the line of the channel is only partially known but a W-N-W trending segment has been defined in the region between Esso exploration oilwell D1-6 and Clark exploration oil well C1-119. Although the course of this segment suggests that both these wells may fall within the channel, the geophysical survey provides no direct proof.

In the case of D1-6, borehole logs and samples are equivocal. Unfossiliferous sands, fine to coarse in grain-size, with some clays extend to 147 feet below ground level (86 feet below sea level) and suggest correlation with the Calanscio Formation rather than the Sahabi channel-fill in view of the paucity of clays. Between 145 ft b.g. l. and 320 feet b. g. l. the sediments are fossiliferous calcareous sandstones and dolomites with some clays and contain a microfauna interpreted by oil company palaeontologists as indicating a Pleistocene age. The character of the sediments does not correspond with that of the channel-fill further upstream, while the age, if correct, does not accord with Barr and Walkers' (1972) hypothesis. Until more positive evidence is available, it seems best to provisionally group these sediments with the underlying limestones, calcareous siltstones and clays of proven Middle Miocene age as has been shown on Cross- Section D-D' (Map-Figure 4).

At C1-119, the lithological log showed that generally coarse grained, poorly sorted sands, with interbedded clays extended from surface to 302 feet below ground level (230 feet below sea level). These sediments could again correspond with either the Calanscio Formation or the Sahabi channel-fill, though the relative abundance of sand would seem to favour the former. The underlying 70 feet of section comprises calcareous sandstones grading to sandy limestones with interbedded shales, which overlies some 710 feet of mainly calcareous shales, fossiliferous in part. Both these units have been referred to the Quaternary by oil company geologists but neither corresponds to the channel-fill sequence upstream, or to the Miocene sequence of interbedded limestones and shales which lies immediately below. It is possible that these sediments represent a marine facies of the channel fill such as might be deposited during a very rapid marine transgression but proof is lacking. Clearly further investigations are required both here and at D1-6, and should groundwater exploration be undertaken in this region, attention should be paid to obtaining further data on the extent, relationships and age of the channel-fill sediments.

With regard to the general question of the age of the Calanscio Formation, it is particularly unfortunate that relationships with the Sahabi Chamel sediments in the north of the Phase 1 area are as yet unclear. Nevertheless, if the near-surface sands in J1-95 do represent the Calanscio Formation, then they must post-date the cutting and at least the initial part of the filling of the channel. Following Barr and Walker (1972), and disregarding the somewhat questionable attributions of Pleistocene and Quaternary ages to the possible channel-fill sediments in D1-6 and C1-119, the formation would, therefore, be younger than early Pliocene in age.

A further pointer to the age of the formation may lie in the marked similarity between the sequence of sedimentary events represented by the erosion and filling of the Sahabi Channel and that reflected by the deposition of the Calanscio Formation. Over much of the Phase 1 area the fluvial, non-marine Calanscio Formation directly overlies marine Lower and Middle Miocene indicating an intervening period of extensive marine regression. The configuration of the basal surface of the Calanscio Formation (Map-Figure 5), particularly in the south and west, is suggestive of a terrestrial erosion pattern, while there are indications of the cutting-out of Miocene strata between neighbouring wells in some locations (Interim Report p. 26). A late Miocene lowering of Mediterranean sea level of the magnitude envisaged by Barr and Walker (1972) would clearly result in terrestrial erosion over a very widespread region and it seems highly probable that the erosion surface at the base of the Calanscio Formation was created at this time.

During the return of the Mediterranean to around its former level in the early Pliocene, deposition would take place first in the deep channels described by Barr and Walker (op. cit) but as base level rose, deposition would spread upstream and finally reach the interfluves. It seems quite likely that much of the Calanscio Formation could date from this period. However the implications of the presence of apparently closed depressions in the basal surface of the Calanscio Formation (Map -Figure 5) must be considered. It is possible that these basins were not, in fact, closed but may have drained northwards through narrow channels, similar in origin and tributary to the Sahabi Channel system, which have not been recognised in the present investigations due to the spacing of borehole control points. Alternatively, the closed nature of the depressions may reflect the effects on the basal surface of tectonic modification or differential compaction. In this case, it would imply that deposition was long contiued, probably extending throughout the Pliocene and into the Pleistocene.

TABLE 1

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

2.2. Hydraulic Properties of the Aquifers

Predictive models used in water resources calculations require among other data, information on the aquifer constants, transmissibility and storage coefficient/specific yield. This information has been obtained by test pumping and lithological sample analysis and the results obtained are discussed below.

2.2.1. Analysis by pumping test data

The preliminary results of pumping test analyses at the 11 sites drilled in the Phase 1 Area are discussed in the Interim Report and the Appendices. Various anomalies were apparent in these results and further analysis has been carried out in order to resolve the anomalies and also to permit more meaningful comparisons to be made with indirect methods of determining the aquifer constants.

The PMM aquifer is 80/100 m thick in the central Phase 1 Area and consists essentially of unconsolidated sands with discrete interbedded clays. Local zones of intermediate gamma values in the sand successions suggest disseminated clay material but in the main the successions show a uniformly low gamma count other than opposite the clay layers referred to. A thicker and more defined clay occurs generally closely beneath the base of the PMM aquifer, particularly in the central Phase 1 Area. At 9 of the test drilling sites, the aquifer tested was the PMM and at the remaining 2, information was obtained on the upper levels of the LMM. The upper levels of the LMM differ in detail from the PMM but do contain a significant percentage of unconsolidated sand and also some interbedded clay layers. The discussion below mainly refers to the PMM aquifer.

The general problems associated with aquifer testing by discharging well methods in a thick, heterogeneous sand/clay sequence were described in the Interim Report and Figure 3 is taken from this document. The associated test conditions include a production well, one or more observation wells specifically drilled for the purpose, plus any existing water wells on the site (commonly two, occasionally three). The latter are commonly screened over a short interval near the base of the aquifer. The main high capacity production wells are cased for 100/150 feet below the water table in order to obtain a fairly substantial available drawdown, and the screened length is of the same order (Table 2). The general hydrogeological conditions at the test drilling sites and the problems in testing and analysis are discussed below.

1. The artesian or leaky artesian response which occurred throughout the pumping tests duration is considered to be related to the nature and distribution of the interbedded clay layers in the aquifer sequence. The majority of drawdown plots showed leaky artesian forms with low r/B values. Storage coefficients were always in the artesian range. Although some drawdown at the watertable did occur in the majority of the tests, the amount was small and it was not considered that leaky artesian analysis would thereby be invalidated. B equals $\sqrt{T/[K'v/m']}$ and is dimensionless. The ratio r/B increases with increasing leakage.

TABLE 2

Phase 1: production well efficiencies

Well	Observed specific capacity [U.S. gpm/ft]	Well Efficiency (percentage)	Screen length ft.
JA-P	4	18	165
JB-P	18	70	203
JC-P	25	69	151
JD-P	23	63	170
JE-P	14	57	160
JF-P	12	58	160

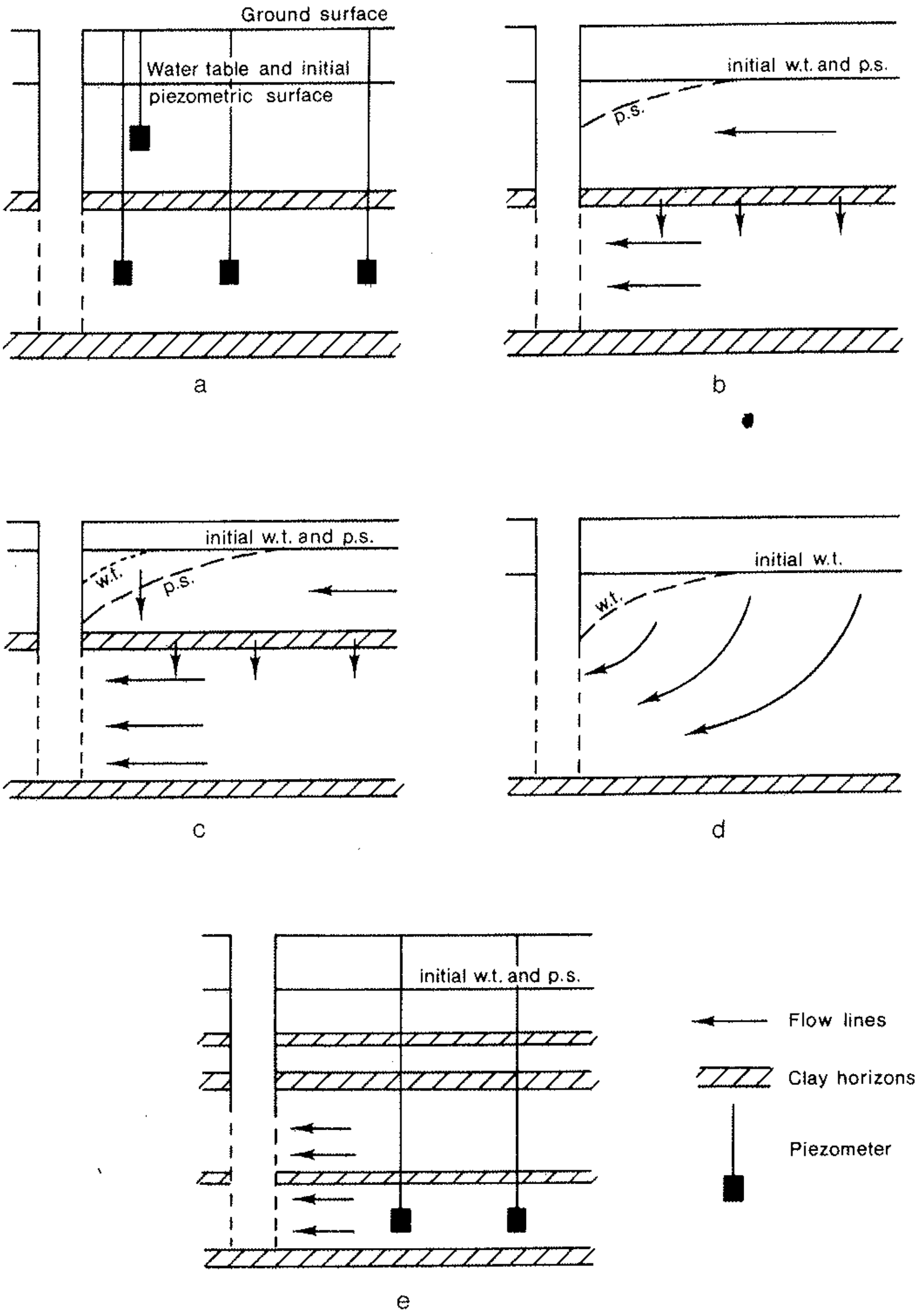


Figure 3. Schematic cross-sections to illustrate conditions in PMM aquifer on abstraction

The aquifer would therefore appear to be responding as a multiple body with an upper unconfined horizon and one or more semi-confined horizons below. The section between the clay layers which define the artesian interval is related to the production well screen interval and is referred to as the responding section [R t]. At most sites, the artesian interval is fairly easy to define. In a few cases, the first clay layer above the production well screen was ill-defined and in consequence the recognition of the exact responding interval less certain. The determined r/B values can be used to calculate the vertical permeability [K'v] of the semiconfining layer located above the production screen interval.

2. Observation well screens may be set at unsuitable intervals so that they do not respond to the total abstraction from the aquifer. In these conditions observed head changes may therefore not be representative of the aquifer response. If the responding section behaves uniformly with horizontal flow as in Figure 3 (a-c), an observation well screen of short length placed in the central section would provide representative drawdowns for aquifer analysis. In the situation 3d, the observation well with a short central screen would need to be sited sufficiently far from the production well for horizontal flow to be obtained. Figure 3e also illustrates a case in which a well screen setting could be inappropriate unless the head relations in the subordinate interval are equivalent to those in the main interval above. In view of the relative uniformity of the sand succession in the PMM the situation may exist. However, any heterogeneity of aquifer characteristics will result in variable abstraction and development of differential head levels within a vertical section. At some sites, there are zones with indications of dispersed clay, particularly near the base of the succession.

There is an additional complication in the uncertainty of flow patterns at all levels, even in a homogeneous aquifer, in the close vicinity of a pumping well. The problems relating to these situations may arise through the use for observation purposes of the existing water wells which are generally screened for a short length near the base of the PMM aquifer.

Analysis of these anomalous situations would be assisted by information from down-hole flow velocity logs but due to instrumental deficiency, measurements were made at only one site in the Phase 1 drilling programme. Flow velocity data can be used to confirm general uniformity of abstraction across the main responding interval and hence the probable 'representativeness' of well water levels in observation wells with limited or localised screen intervals. Alternatively the abstraction from the particular subsection can be used for independent analysis of the sub-section, on the assumption that it will respond independently other than by leaky interaction across the boundary clay layers. Particular sites in which this situation is thought to occur include JA and JF, and the details are discussed below.

3. Well 'storage and skin' effects which are here defined for convenience as 'well' effects can give reduced drawdowns. Inertial effects are known to be of small significance and can be disregarded. Storage effects increase with the diameter of the well. Skin effects give a locally reduced hydraulic connection with the aquifer and likewise result in reduced drawdowns. Strictly speaking the skin effect is related to damage of the aquifer by drilling, notably for example by excessive mudding of the formation. The effect can however also occur as a result of the well screen being set in a clayey horizon. This can be avoided by careful correlation of the screen setting with lithological samples and a gamma-ray log. Where the aquifer has been damaged by drilling, well completion should continue until adequate hydraulic continuity exists. A production test gives some indication of the degree of completion but a preferred method is by slug testing in which the rest water level is changed suddenly, usually by addition of a known volume of water, and the subsequent return of the levels to equilibrium is monitored. The recovery plots are matched against a set of type curves (Cooper, Bredohoeft, and Papadopulos, 1967) and a value of transmissibility calculated. The type curves have a range of values [α] related to the coefficient of storage. The authors state that for α less than 10^{-5} analysis indicates that, if the value of α for the chosen type curve is within two orders of magnitude of its actual value, the error in the determined T would be less than about 30%. The calculated transmissibility is mainly representative of the material close to the screened section. Assuming therefore that some indications of the transmissibility of the screened section are available e. g. indirectly from sample analysis, slug test results can be used as an indication of well development.

'Well' effects result in reduced drawdowns in the observation well as compared with those in the aquifer adjoining the well. The differences decrease with time and the observed plot will approach the true plot asymptotically, deviations always being negative. Various methods of correcting the observed drawdowns for 'well' effects have been tried. An empirical method was first used in which the correction was related to the rate of recovery shown by the slug test plot. A check on the method by Dr. R. Kitching of the IGS, using a computer modelling technique (verbal comm.) indicated that the corrections were excessive. The computer technique itself could be adapted to obtain corrections but the method is time consuming and not fully established. A second empirical method has been applied based on the assumption that the observed plot of drawdowns during a pumping test is asymptotic to the true plot as a result of the error decreasing with increasing time. The degree of deviation may be apparent from the curve fitting alone but can be generally confirmed by the slug test transmissibility results, which indicate the magnitude of the skin effect. This second method works well with an artesian or leaky artesian plot with low r/B but becomes more problematic with curves of higher r/B values. For the former cases, additional confirmation should be provided by the semi-log plots of the later time-drawdowns. The actual drawdown plots will eventually be made available.

All pumping test results have been reanalysed using corrected drawdowns where necessary and in many cases, anomalies have been resolved. The results of the slug testing are shown in Table. 3. The individual site analyses are discussed below and the average values of aquifer constants based on the most reliable results are given in Table 4. In general it has been found that under the conditions of the aquifer tests and in relation to the diameter of the observation well, radial distance etc., corrections of only a minor order appear to be required when the screened section permeability is within 10% of the probable aquifer permeability and assuming that the screen is set within an 'average section'. It is therefore most important to ensure firstly that observation well screens are set in sections of average or higher than average permeability, and secondly that completion is adequate to ensure sufficient hydraulic continuity within the limits discussed. It is also important to ensure that the screens straddle the main responding interval, unless the general homogeneity of the aquifer indicates that this requirement is unnecessary. Flow velocity logs should be regarded as an essential part of any production test.

4. Drawdown errors may be also due to intercommunication between the responding and non-responding sections other than through intervening clay layers. Such intercommunication could occur if screens are set in both sections in a single well. JB-01 was a case in point and because no drawdowns occurred during the test in the upper non-responding interval, the observed drawdowns relating to the main responding interval were reduced by inflow from the higher level. Additionally, some intercommunication between horizons of differing responses is possible outside the casing With recently drilled wells, especially those drilled with bentonite mud, a blank cased section is likely to remain open for a lengthy period following completion. Should an aquifer test be carried out during this period, the possibility exists of open hole intercommunication outside the casing. In any event there would be increased well storage effects due to the large volume of water stored in the open hole section. Conclusions to be drawn from these considerations are that care must be taken during drilling to avoid mudding-up the aquifer even in the case of observation wells, that general de-mudding with use of dispersants should be carried out throughly and preferably a cement plug should be set at an appropriate clay layer to prevent openhole communication. Lengthy swabbing and development of the screened sections is desirable to assist de-mudding and collapse of the formation around the screen and casing.

2. 2. 2. Analysis by grain size distribution

The PMM aquifer consists of unconsolidated sands with clay material generally limited to discrete layers. Conditions are therefore suitable for evaluating the aquifer constants, permeability and specific yield, from grain size distributions. The importance of obtaining representative samples was therefore stressed in the test drilling programme. The advantages of the possession of a good correlation of aquifer constants with rotary drilled sample material are manifold.

For permeability, the method developed by Masch and Denny (1966) was utilised. These authors correlated permeability as determined by a constant head permeameter with average size, dispersion, skewness, peakedness and modality of the sample distributions. They have provided a set of prediction curves incorporating only the average size and dispersion because it was found that these parameters best described the relationship. The graphs relate the median D50 size in phi units to dispersion. Phi units are the negative of the logarithm to the base 2 of the particle diameter in mm. Dispersion is measured by the inclusive standard deviation which is given by the following expression.

$$\sigma_I = (\phi 84 - \phi 16)/4 + (\phi 95 - \phi 5)/6.6$$

The correlation between these two parameters was established on 12 samples of washed Colorado River sand providing a range of permeabilities from less than 100 U.S. gpd/ft^2 to more than 2000 US gpd/ft^2 and of median D50 diameters from -0.5 to +3.5ϕ. The predictive curves were developed by linear interpolation and replotted on semi-log paper.

Data from the Phase 1 lithological samples

TABLE 3

Phase 1 observation wells: slug test data

1	2	3	4
JA-WW south	5.12	-	-
JB-02 (short string)	4.34	14.0	0.31
-02 (long string)	2.15	14.6	0.15
-WW North	18.34	-	-
-WW South	0.93	-	-
JD-01	7.36	11.0	0.67
-02	2.43	7.3	0.33
JE-01	23.14	26.5	0.87
-02	8.85	7.6	1.16
-WW South West	1.16	12.8	0.09
-WW North West	28.60	3.7	7.73
J [A1-LP5C]short string	0.43	3.7	0.12
- longstring	18.98	20.9	0.91
- WW North	16.2	3.4	4.76
J [A1-LP3C] short string	3.17	-	-
- long string	10.75	9.0	1.19
-WW South	50.63	22.3	2.27
-WW East	69.43	27.1	2.56
J [C1-95] -WW East	13.89	-	-
- WW Central	0.25	13.7	0.02

Columns:-

1. Well location
2. Transmissibility in m^2/day
3. Screen length in metres
4. Calculated permeability, screened section, in m/day

TABLE 4

Well site details and aquifer characteristics based on pumping tests and grain size analysis

	1 Rt	2 Rte	3 KR_te	4 TR_t	5 T	6 S $(x\ 10^{-4})$	7 U_t	8 U_te	9 KU_te	10 TU_t
JA	327 - 566	170	228	481	1743	-	252 - 327	63	420	329
JB	368 - 566	152	264	498	616	2.4	267 - 368	81	No samples	267
JC	248 - 518	232	300	866	1541	6.4	-	-	-	-
JD	268 - 506	209	331	858	867	5.0	229 - 268	23	385	109
JE	334 - 522	161	312	623	611	2.2	286 - 334	37	284	121
JF	338 - 496	141	320	560	587	3.0	249 - 338	75	401	373
J[KK1 - 12]	348 - 501	138	355	608	1054	2.4	219 - 348	75	605	563
J [F1-97]	309 - 501	170	315	665	841	3.7	164 - 309	105	445	580
J [A1-LP5C]	-	-	-	-	-	-	287 - 320	33	280	113
J[A1-LP3C]	425 - 509	71	338	298	250	2.6	275 - 425	137	255	433
J[C-95]	124 - 301	152	346	653	784	1.8	301 - 700	130	328	529

Columns:-

1. Rt: responding interval with values in feet below ground level
2. Rte: effective thickness of responding interval (total thickness minus clay)
3. KR_te: permeability in USgpd/ft ^{2} based on grain size analyses
4. TR_t: transmissibility based on 2 and 3 expressed in m^2/day
5. T: transmissibility based on pumping test analysis in m^2 /day
6. S: storage coefficient on pumping test analysis (dimensionless)
7. U_t: thickness in feet below gl of non-responding interval
8. U_te: effective thickness in feet
9. KU_te: permeability in US gpd/ft^2 based on grain-size analyses
10. TU_t: transmissibility in m^2/day

NB: Ut at A1-LP5C is in PMM; Both R_t and U_t at A1-LP3C are in LMM; U_t at C1-95 is in LMM.

were initially plotted on semi-log paper with the log of the particle size in microns versus the percentage retained. Later plots utilised the ∅ scale and probability paper. In calculating the average permeability of any section, the permeability of each 10 foot sample was obtained by plotting the relevant paramenters and then calculating the average. A detailed sample of a particular site, JF, is given below in Table 6 and Figure 6. In Table 4, only the final calculations for the other sites are listed.

Specific yield is defined as the ratio of the volume of water that a saturated material will yield by gravity to the total volume of the material. All aquifer tests carried out to date have provided values indicating an artesian storage coefficient which will apply to the conditions operating in the short term tests but not in the long term when it is believed that drainage under water table conditions will occur. For predictions under those conditions, values of specific yield are required. Specific yield can best be obtained during long-term abstraction regimes when drawdowns at the water table can more accurately be related to abstraction. Short-term tests are difficult to analyse accurately due to the added complication of artesian storage release within the aquifer's responding interval. During longer term tests, this factor will become of little significance. An added complication which must be avoided or accounted for is possible recycling of the abstracted water. When reliable values of specific yield, based on long-term tests, become available, a correlation with grain size analysis data must be sought and in the circumstances is likely to be possible. Until direct measurements do become available, specific yield may be estimated by a correlation established perferably in a similar sedimentary environment. Preliminary studies have been made by plotting grain size analyses on a diagram prepared by Klein (1967, Fig 9A). The diagram relates the median grain diameter in microns and the sorting factor $\sqrt{D10/D90}$. The diagram (partially reproduced below, text figure 8) covers the range from clay to coarse sand and shows an oval field transected by lines of specific yield and permeability. The oval field is based upon tests of more than 1000 core samples. The samples are from alluvial basins in the Santa Margarita Valley California but in the publication referred to no other data on sedimentary characteristics are provided. The information available is insufficient to allow a detailed assessment to be made of the degreee of validity of the correlation or of the degree of similarity of the Santa Margarita sediments with those of the Libyan aquifers under discussion. The large number of samples used is significant and the 16 illustrative samples shown in the original figure correlate well. The upper thirty feet below the water table at each test site was analysed in the manner described for each 10 foot sample. Since in all cases, the range of values of both the median diameter and sorting coefficient at each site was small, average values for the 30 feet are shown in Table 5 and plotted in the Text figure 8. Most of them fall within the oval field and all show specific yield in excess of 30%.

2. 2. 3. Test drilling site analyses

Basic details of the test sites drilled in the Phase 1 Area are contained in the Appendices to the Interim Report and further result compilations, following upon re-analysis of the data collected, are provided in Tables 2-4 of this report. Data summaries for each site are given below, commencing with JF for which a fuller evaluation is provided.

2. 2. 3. 1. Site JF (Appendix 6, Interim Report)

Figures 4 and 5 from Appendix 6 of the Interim Report are reproduced here. Table 6 gives various site details, Table 7 a summary of the aquifer pumping test results, and Figure 6 a correlation of depth, lithology, grain size permeabilities and screened intervals. Five observation wells are located at this site, four of which are screened in the main responding interval, and the fifth, JF-01 (short string), at a high level near the water table. It should be noted that the screen of the long string of JF-01 straddles all clay layers within the main responding interval but those of the three water wells (WW's N, S and E) occur below the highest clay layer within that interval.

Slug tests were carried out on all five wells but screen-aquifer transmissibilities were not calculated. With the exception of the short string of JF-01 and to a lesser extent WW South, all observation wells showed a satisfactory response to slug testing, indicating that drawdown corrections were not generally warranted. All wells showed marked barometric responses.

Drawdown data for all wells gave leaky artesian plots with intermediate leakage coefficients. Minor drawdown occurred in the short string of JF-01 indicating movement from the water table, thus confirming leaky or unconfined conditions. The re-analysed results of the plots from the wells in the responding interval are shown in Table 7. The various values of T and S are generally comparable but with those from JF-01 rather higher. Although the screen settings of the three Company water wells occur below an

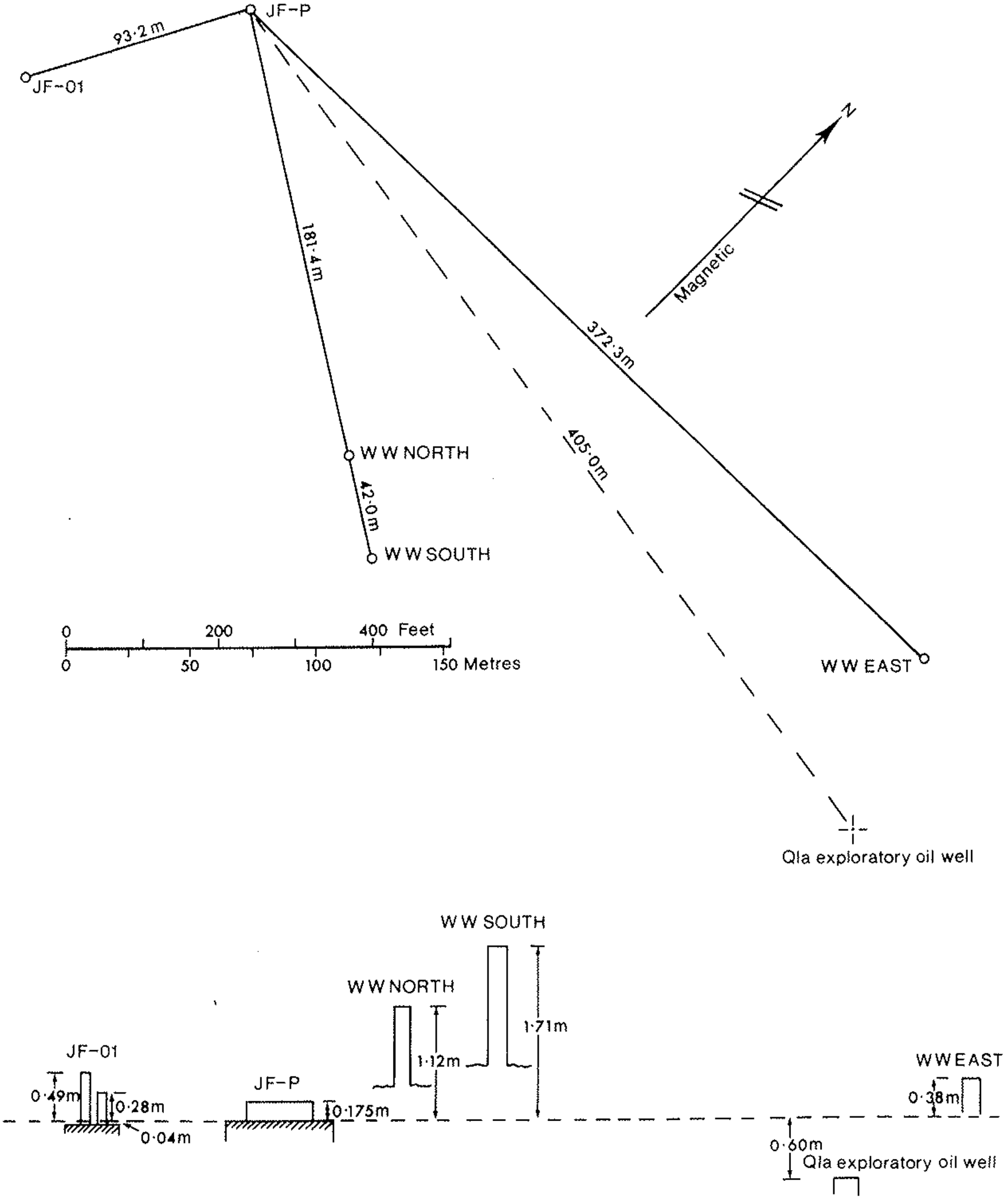


Figure 4. Site JF: Site plan and elevations

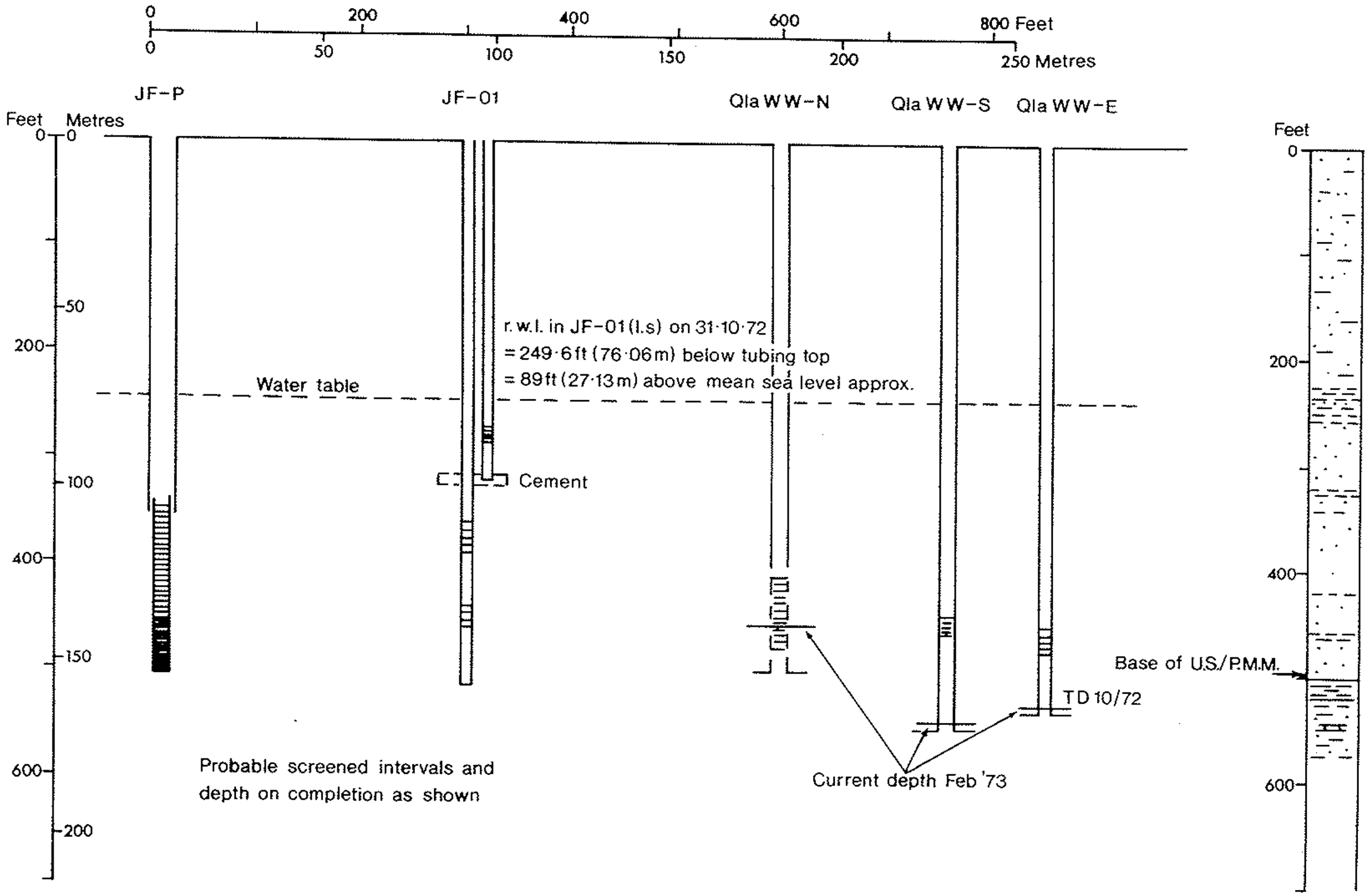


Figure 5. Site JF: Lithology and cross-section

intermediate clay layer within the assumed responding interval, the grain size permeabilities (column 3, Figure 6) accord with probable uniformity of head values in a vertical section and therefore generally validate the plots of these wells in relation to the entire responding interval. A general check on this possibility was carried out using relative grain size permeability and appropriate thickness to calculate proportionate abstraction from the aquifer sections on the assumption that JF-01 related to the entire responding section, and the Company water wells to the restricted subsection deeper than 395 feet below ground level (bg l). These calculations indicate an abstraction of 25.5 litres/sec from the deeper interval and 47.3 litres/sec from the full responding interval. The transmissibility of the lower section is recalculated as 305m ^{2}/day and the average permeability of the component sands to be 11.91m/day or 293 U.S. gpd/ft ^{2}, which compares very closely with the grain size computation of 289 U.S. gpd/ft ^{2}. Applying the total abstraction to the JF-01 drawdown data, the resulting transmissibility is 741 m ^{2}/day.

The average permeability based on the JF-01 plots is 17.2 m /day equivalent to 422 U.S. gpd/ft ^{2}, which is somewhat higher than the grain size average of 320. The discrepancy may indicate that the JF-01 data are providing an exaggerated value of transmissibility or that the responding interval is wider than estimated. Well efficiency based on a T value of 560 m ^{2}/day is 58% whereas on a T value of 741 m ^{2}/day it is 44%. The former is more closely comparable with other Phase 1 production wells and tends to confirm its greater likelihood. The value of 560 m ^{2}/day is based entirely on grain size computations but is very closely similar to the pumping test results from the existing wells data (Table 7).

The calculation of the vertical permeability of the semi-confining layer is subject to uncertainty as to how far the intermediate clay layer has influenced the drawdown plots of the existing wells. On the assumption of a two metre thickness above 338 feet bgl, JF-01 data and those from the Company water wells give comparable results around 0.0015/0.0017 m/day. If a similar computation is applied to the intermediate layer the value derived is 0.0007 m/day.

2.2.3.2. Site JA (Appendix 1, Interim Report)

JA-P was drilled with bentonite mud and during drilling excessive mudding up of the aquifer occurred. Additionally, bridging of the gravel pack resulted in excessive sand production during discharge. Despite prolonged development, including acidising, the well produced poorly with an eventual specific capacity of 4 U.S. galls/min/ft.

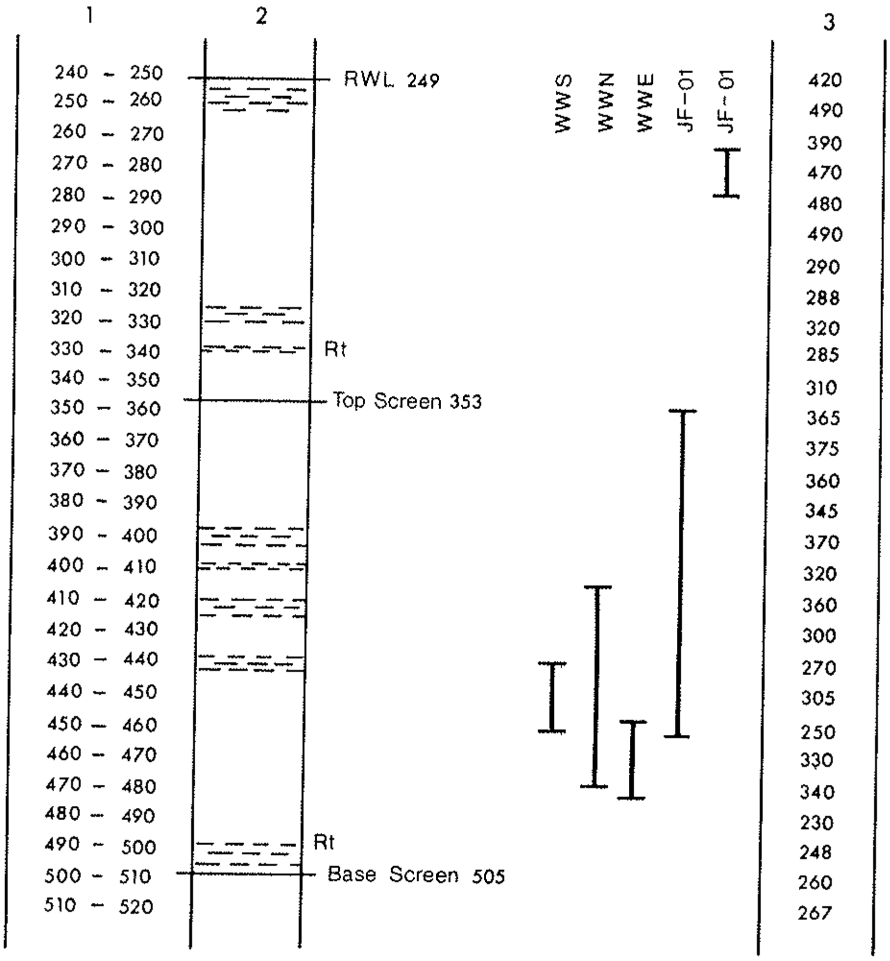
During the aquifer test, observation well JA-01 could not be used due to sanding-in. The two Company water wells therefore provided the only drawdown data. No details of screening are available in the Occidental Company records but the wells presumably have short lengths of screen located near the base, i.e. above 515 feet bgl.

The drawdown plots showed leaky artesian forms with low r/B values. The apparent transmissibility, calculated on the assumption that the drawdown data relate to total abstraction is 1743 m ^{2}/day with an implied well efficiency of 5%. The results are anomalous and the situation occurring in figure 3 (e) is thought to have prevailed. The grain size permeability values indicate heterogeneity between sections above and below the intermediate clay layer (437-455 feet bgl) with average values of 267 and 170 U.S. gpd/ft ^{2} respectively. Head levels in the lower section are therefore unlikely to correspond with those in the upper, particularly at this low rate of pumping, and with increased heterogeneity possibly related to differential aquifer damage. True transmissibilities have therefore been estimated on grain size data alone and even on the assumption of a value of 481 m ^{2}/day for the responding interval, the well efficiency still attains only 18%, indicative of extremely poor development.

2.2.3.3. Site JB (Appendix 2, Interim Report)

Two Company water wells [WW's North and South] and JB-02 (long string) had screening suitable for observation purposes. The short string of JB-02 was set in the upper levels of the aquifer near the water table and showed no drawdown throughout the aquifer test, although the slug test showed it to be in adequate hydraulic continuity with the aquifer. Of the three wells screened in the main responding interval, WW South and to a lesser extent JB-02 (long string) required drawdown corrections due to poor well-aquifer continuity.

The results of Test III were mainly utilised in the final analysis since discharge rates were maintained more constantly than in the earlier tests. The results are summarised in Table 8. The results are closely comparable despite the fact that the screens of the Company water wells occur below significant intermediate clay layers. However, grain size permeability values (full list not shown) are closely consistent throughout the main responding interval and it



Columns:-

1. Depth interval in feet below ground level
2. Clay layers and site conditions, including screen setting of production well
3. Permeability in U.S. gpd/ft^2 based on grain size analyses

I Screened intervals in observation wells

Figure 6. Site JF: Hydrogeological correlation

TABLE 5.

Specific yield of upper 30 feet of PMM and LMM aquifers based on grain size distributions

1	2	3	4	5	6
JA	480	1.9	30+		1
JC	628	3.5	30+	-	2
JE	303	2.2	30+	246	3
JF	530	2.3	30+	450	4
J (KK1-12)	857	2.4	30+	860	5
J (F1-97)	458	2.3	30+	425	6
J (A1-LP3C)	309	3.1	30+	187	7
J (A1-LP5C)	279	2.1	30+	279	8
J (C1-95)	310	1.9	30+	-	9

Columns:-

1. Well site
2. Median diameter in microns
3. Sorting coefficient D10/D90
4. Specific yield (after Klein 1967) - percentage
5. Permeability (based on D50 and dispersion) in US gpd/ft^2
6. Sample number as shown in reproduced plot of the Klein (1967) diagram (see Figure 8)

TABLE 6

JF Site details

(i) Elevations in feet above mean sea level

Q1A - 103	336
Survey datum	338
JF-01 ground level	337.8
JF-01 tubing top	338.6
WW North casing top	339.7
JF-P casing top	338.5
JF-P ground level	338

(ii) Depths in feet:-

RWL below tubing top in JF-01	249.6
Top of screen, JF-P below ground level	353
Base of screen, JF-P below ground level	505
Responding section below 01 g 1, (R_t)	338-496
Non responding section below 01 g 1, (U_t)	49-338
Significant clay layers in feet below ground level at JF-01	1. 251-259
	2a. 322-326
	2b. 336-338
	3. 394-400
	4. 404-407
	5. 417-422
	6. 434-438

(iii) Thickness in feet

R_t	158
R_t effective (minus clay)	141
U_t	89
U_t effective	75

(iv) Average permeability in US gpd/ft^2

R_t effective	320
U_t effective	401

(v) Transmissibilities in m^2/day

R_te	560
U_te	373

TABLE 7

Site JF: Summary of aquifer pumping test results

Well	T m^2/day	S x 10^{-4}	Analysis
JF-01 (long string)	739	4.1	DD/LL; r/B = 0.4; Kv = .0017 m/day
	744	5.0	DD/SL
Average	741	4.6	
W W East	592	2.3	DD/LL; r/B = 0.4 Kv = .0015 m/day
	716	1.7	DD/SL
Average	656	2.0	
W W South	464	2.2	DD/LL; r/B = 0.316
	594	1.7	DD/SL
Average	529	1.9	
W W North	479	2.5	DD/LL; r/B = 0.316
	556	1.8	DD/SL
Average	517	2.2	
Distance-drawdown	492	4.3	
Average all wells and distance-drawdown	587	3.0	

can be assumed that this accordance reflects uniformity of head changes in a vertical plane.

TABLE 8

Site JB: Summary of aquifer pumping test results

WELL	T m^2/day	S x 10^{-4}	ANALYSIS
JB - 01 (long string)	584	2. 5	Artesian
WW North	642	1. 3	Leaky Artesian r/B = 0. 1
WW South	623	3. 4	Leaky Artesian r/B = 0. 1
Average	616	2. 4.	

The artesian plot of JB-01 (long string)accords also with the absence of drawdowns in the short string. The leakage coefficients of the Company water wells plots could not be used to determine the vertical permeability of the semi-confining layer above the main screen interval since they almost certainly reflect changes across one of the intermediate layers.

The well efficiency based on the average pumping test transmissibility is 70% (Table 2). Total transmissibility based on grain size determinations alone is 775 m^2/day. Using the pumping test data together with the grain size evaluation for the non-responding layer, it is 883 m^2/day. The grain size results compare very closely with the pumping test value.

2. 2. 3. 4. Site JC (Appendix 3, Interim Report)

At this site there is a considerable discrepancy between the grain size and pumping test transmissibility results. The apparently low well efficiency of 44% based on the latter value suggest that the pumping test transmissibility value is excessive, and the suggestion is confirmed by the mathematical model values which correspond more closely to the grain size analyses.

The two Company water wells are screened close to the base of the aquifer. JC-01A was initially screened at two levels, one high and the other low, the latter corresponding with the screened intervals of the Company water wells. Subsequently a packer was inserted in the casing in order to separate the two screen intervals. The measurements in the annulus, corresponding to the upper level, were somewhat suspect due to cable stretch. Additionally, the lack of cement plug in the hole may have resulted in communication between the two levels outside the casing, although there is no certainty of this.

Five clay layers occur within the aquifer, all of which lie above the screened sections in the Company water wells and above the lower screen in JC-01A. The two upper clay layers are ill defined and in consequence the responding section is uncertain. Basic details including the grain size permeabilities are shown in Table 9.

Since the well screens in the responding interval all occur below 449 feet, it is obvious from the heterogeneity of the section that the head values below this level are unlikely to be representative of the entire aquifer and in consequence the aquifer test results must be viewed with caution.

No slug tests were carried out in the observation wells but all were quite highly productive after cleaning. Additionally the drawdown plots clearly follow leaky artesian trends with low r/B values. The poorly defined clay layers in the high levels and the almost immediate response from the upper screen of JC-01A suggest very leaky or unconfined response which adds weight to the concept of localised response of the other observation wells.

The average transmissibility quoted in Table 4 of 1541 m^2/day is therefore not regarded as reliable. More probable values can be obtained from the grain size analyses with a responding section regarded as either the entire aquifer or the section below 338 feet. The sectional results are shown in Table 9, the combined values in Table 4. Using the overall transmissibility of 866 m^2/day, the well efficiency is computed as 69%; using the sectional value of 620m^2/day, it is 95%. The former value is preferred and it is concluded that the aquifer in this instance responded in basically unconfined fashion.

TABLE 9

Site JC: Permeability and transmissibility values based on grain size analyses

(a) Non-responding section.					
1	2	3	4	5	6
248 - 308	60	53	210	11,130	
308 - 338	30	23	379	8,717	
				19,847	246
(b) Responding section					
338 - 356	18	17	187	3,179	
356 - 413	57	48	325	15,600	
413 - 449	36	22	183	4,026	
449 - 518	69	69	393	27, 117	
				49, 922	620

Columns:-

1. Depth interval in feet, below ground level
2. Thickness in feet of intervals
3. Thickness of intervals less thickness of clay layers occurring within interval
4. Average permeability in U. S. gpd/ft^2 based on grain size data.
5. Transmissibility in U. S. gpd/ft
6. Total transmissibility in m^2/day

2. 2. 3. 5. Site JD (Appendix 6, Interim Report)

At this site no Company water wells were available and two observation wells were drilled additional to the production well. Drilling of the observation wells was with bentonite mud and they required lengthy development. Final results were still poor as evidenced by the slug tests (Table 3). Considerable corrections were therefore required for the drawdown data.

On the assumption that the observation wells were responding to the total abstraction from the aquifer, final re-analysis gives the following results in Table 10.

The distribution of the screened sections of the observation wells is shown in Figure 6 of Appendix 4 of the Interim Report. Grain size variations do occur but are not of a great significance and the general indications in Figure 6 are confirmed by the grain size permeabilities which have been calculated for each 10 foot sample (full details not shown). The first significant clay layer above the screen level occurs between 258 and 268 feet bgl, and this was assumed to define the upper limits of the responding interval. Some less defined layers occur lower down below the uppermost screen of JD-01, but above the main screen of JD-02. The general correlation of the results of the two wells does however indicate concordance of head levels whether in consequence of the ineffectiveness of these less-defined layers or the general uniformity of permeability. The grain size transmissibility calculated on the basis of the responding section assumed above, is 858 m^2/day which correlates extremely closely with the average pumping test value of 867 m^2/day. (Table 10). The well efficiency based on the pumping test data is determined as 63%. The total transmissibility calculated using grain size data alone is 968 m^2/day, or 976 m^2/day if the two analytical methods are combined.

TABLE 10

Site JD: Summary of aquifer pumping test results

WELL	T m^2/day	S x 10^{-4}	ANALYSIS
JD -01	974	5.3	Leaky artesian; r/B=0.2 Kv = .0084
JD -02	760	4.8	Leaky artesian; r/B=0.1 Kv = .0085
Average	867	5.0	

2.2.3.6. Site JE (Appendix 5, Interim Report)

Two of the three Company water wells occurring at this site were accessible for drawdown observations. WW North-West was screened in the mid-levels and WW South-West in the lower levels of the aquifer (see Figure 5 in Interim Report, Appendix 5). Well JE-01 was drilled with bentonite mud and completed with a wide spread of screens across the main production well interval. JE-02 was drilled with Revert mud and completed with a short screen open at the water table. Slug tests showed that all except WW South-West had satisfactory continuity with the aquifer. Both 01 and 02 had high barometric efficiencies but no effects were recorded in the two Company water wells.

Grain size permeabilities are fairly regular throughout with some rather lower values immediately below the water table and near the base of the aquifer. Four clay layers occur within the aquifer. The screens in JE-01 straddle the lower three layers, as does also the production well screen. The upper clay layer from 322 to 334 feet bgl should define the upper limit of the responding section. WW North-West is screened between clay layers 2 and 3 and WW South-West between clay layer 3 and the base of the aquifer. The general uniformity of permeabilities based on the grain size data should have resulted in uniform head levels in the vertical section and accordingly provide consistent values of the aquifer constants.'

The results of the actual tests are anomalous as will be apparent from Table 11. The Company water wells give comparable results but JE-01 a very much higher transmissibility. Well efficiency calculated on the basis of the average T value for the data from the Company water wells is 57% whereas an anomalously low value would result if the higher transmissibility based on the JE-01 result is used. All wells showed either artesian or leaky artesian plots. The leaky plot wouldgive a vertical permeability of the semi-confining layer as 0.0007 m/day but not much significance can be attached to the result in view of the limited screening in relation; to the main responding interval. Drawdowns of small magnitude occurred at the water table.

The grain size results provide a calculated transmissibility of the responding section of 623 m^2/day which compares closely with the average values from the Company water well plots of 611 m^2/day, and further confirms their validity. Total transmissibility based on the grain size data alone is 744 m^2/day whilst using the results from the Company wells combined with grain size data, it is 732 m^2/day.

2.2.3.7. Site J(KK1 - 12) :(Appendix 8, Interim Report)

This site is the most north-easterly location drilled in the central Phase 1 area. The two Company water wells were used for drawdown observations and the test well for production by air lift. No slug tests were carried out but both wells gave satisfactory production on cleaning, which is not surprising since both had recently been under production.

The aquifer lithology is shown in Figure 3 of Appendix 8 of the Interim Report. The upper 129 feet below the water table is composed of more than one third clay: the lower 152 feet is; predominantly sand and it is in this section that all screens were set. Grain size permeabilities are moderate and uniform in the lower horizon, averaging 355 U.S. gpd/ft^2. In the upper clayey section, values are more variable and the average is higher (605 U.S. gpd/ft^2).

The aquifer test showed, as was to be expected., plots of artesian or leaky artesian form with low r/B values. Some uncertainty of the latter condition relates to a fall in pumping rate at the time leakage became 'apparent'. The results of the analyses quoted in Appendix 8 show minor discrepancies between the log-log and semi-log plots. On re-analysis and application of a correction to the first 10 minutes of drawdown, the results become consistent and the average values for each well are shown in Table. 12.

TABLE 11

Site JE: Summary of aquifer pumping test results

WELL	T m^2/day	S x 10^{-4}	ANALYSIS
JE-01	1584	4.5	Theis
WW NW	637	1.8	Theis
WW SW	585	2.6	Leaky artesian, r/B=0.1

TABLE 12

Site J(KK1-12) Summary of aquifer pumping test results

WELL	T m^2/day	S x 10^{-4}	ANALYSIS
WW East	1023	3.5	Leaky Artesian
WW West	1086	1.3	Leaky Artesian
Average	1054	2.4	

TABLE 13

Site J(F1-97): Summary of aquifer pumping test results

WELL	T m^2/day	S x 10^{-4}	ANALYSIS
WW North	911	4.1	Leaky Artesian
WW South	771	3.4	Leaky Artesian
Average	841	3.7	

The transmissibility calculated on the basis of the grain permeability values are not comparable. The responding section has a calculated value of 608 m^2/day and the non-responding section of 563 m^2/day. Total transmissibility is 1171 m^2/day.

The anomalous relationships are difficult to explain. The drawdown plots are well defined and lithological definition of the responding section is also good. Other than these factors, lack of correlation could only be explained by an error in the quoted screening, or as a consequence leakage down the outside of the casing from upper to lower levels of the aquifer during testing.

2.2.3.8. Site J(F1-97) (Appendix 7, Interim Report)

This site was also tested by air lift pumping using the test well for production and with drawdown data obtained from the two existing wells. The test was generally unsatisfactory with variable pumping rates and excessive sand production, and the drawdown plots are poorly defined. Some 5/6 clay layers are scattered throughout the sequence and the screens in the observation wells occur below a significant clay layer within the main responding section. Grain size permeabilities in the whole responding section average 315 U.S. gpd/ft^2. Whereas in the lower section in which the screens occur, it is 262 US gpd/ft^2. This minor variation could result in discrepancy between aquifer test and grain size results.

A summary of the aquifer test results based on re-analysed plots is shown in Table 13.

The drawdown plots showed high leakage coefficients (0.4/0.6) which may be due to the screen setting in relation to an intermediate clay layer. Transmissibility values are therefore likely to be too high and a reduction would bring them more into line with the grain size analyses results. The latter do compare fairly closely with the pumping test results, with the main responding section having a calculated value of 665 m^2/day and the upper section of 580 m^2/day. In view of the uncertainties of the aquifer results the grain size values are regarded as more reliable and the total transmissibility based on this data is 1245 m^2/day.

2.2.3.9. Site J (Al-LP5C) (Appendix 9, Interim Report)

At this site, test drilling was designed to prove the hydraulic discontinuity between the PMM and LMM aquifers and the minor air lift pump test was of secondary significance. A head difference of 131 feet between the two aquifers was proved to occur under static conditions and no apparent drawdowns occurred in the PMM on abstraction from the LMM. The PMM aquifer is 33 feet thick at this site and the grain size permeabilities indicate a transmissibility of 113 m^2/day.

2.2.3.10. Site J (A1 - LP3C) (Appendix 10, Interim Report)

The static water level at this site occurs close to the base of the PMM and the aquifer test was therefore carried out solely within the Lower and Middle Miocene. Test drilling has extended through a significant sand section occurring in the LMM down to 530 feet below ground level. The results are significant because this sand horizon is in effective continuity in this area with the PMM aquifer.

Grain size permeabilities showed no great variation throughout the aquifer section penetrated by drilling. Four clay layers occur, two within the probable responding section. The clay layer thought to define the top of the responding section is only four feet thick and the feature may account for the rather variable drawdown plots with high leakage coefficients. Pumping was by air lift from WW North-West and the screens in the three observation wells straddle the two clay layers in the assumed responding interval.

Pumping test procedures were not satisfactory and the rate of discharge varied. Plots of water level data derived from the long-string of J(Al-LP3C) were ignored because of their irregular form and the summary of the results from the two Company wells is given in Table 14.

Although the test conditions were not satisfactory, the results give a fairly close comparison with grain size analysis. Transmissibility of the responding section is calculated to be 298 m^2/day and of the overlying section to be 433 m^2/day, making a total of 731 m^2/day.

TABLE 14

Site J(Al-L P3C): Summary of aquifer pumping test results

WELL	T m^2/day	S $\times 10^{-4}$	ANALYSIS
WW South	251	2.9	Leaky Artesian : r/B=1.5
WW NE	249	2.6	Leaky Artesian: r/B=0.5
Average	250	2.8	

2. 2. 3. 11. Site J (C1-95) (Appendix 11, Interim Report)

At this site, the base of the PMM is at 300 feet below ground level (154 feet below sea level). Well J (C1-95) was drilled to 700 feet with the upper section of the LMM (originally referred to as the Aklash Formation) composed mostly of carbonate rocks and clays but with some interbedded sand formations. Static head levels within the upper LMM are co-incident with those in the PMM.

Pumping was carried out in J (C1-95) after the well was plugged back to the base of the Calanscio Formation (PMM). Abstraction was thus effectively limited to the latter formation and observational data obtained from two Company water wells which are screened in this interval.

Grain size permeabilities are fairly regular throughout the sandy sections of the aquifer but some carbonate rocks also occur, particularly in the upper levels near the water table. Two prominent clay layers occupy intermediate levels and the screens of the Company water wells straddle the lower but occur below the higher level clay layer. Uniform permeability values favour uniform head changes in a vertical plane, but there is the added complication of heterogeneity due to local carbonate occurrence.

Slug tests showed good response from WW East but poor from WW Central. After re-analysis of the drawdown data and correcting where necessary, the results from the two Company water wells are fairly consistent (Table 15). The plots are leaky artesian with intermediate r/B values. The latter features suggests the operation of a clay layer within the responding section but above the screened intervals and with head differentials developing during abstraction and resulting in 'leaky' type plots.

Transmissibility of the main responding section which here includes the whole PMM, is 653 m^2/day. The difference between this value and the aquifer test result is not great but for the reasons quoted above, the slightly lower grain size value is to be preferred.

The section of the LMM drilled contains approximately 130 feet of unconsolidated sands. Average permeability from grain size analysis is 328 U.S. gpd/ft^2 and transmissibility 529 m^2/day. Total transmissibility based on grain size values is 1182 m^2/day.

2. 2. 4. Discussion of results

2. 2. 4. 1. Permeability/transmissibility

In Table 16, the transmissibility of the responding intervals at 10 Phase 1 test sites based on grain size and pumping test analyses are compared. In 7 of the 10 cases, the grain size value is within 21% of the pumping test value and in 3 of the 7, the percentage difference is within 5%. (see also Figure 7). Of the three sites with larger differentials, at JA and JC, reasons are apparent for preferring the grain size results to the pumping test values. Taking into account such factors as production well efficiency and comparison with model values (Table 17), it seems likely that the grain size results would be within the same order of comparison as the other 7. At KK1-12, no obvious explanation of the anomaly exists in the conditions of the pumping test. It should be noted however that the grain size total transmissibility value accords more closely with the model value.

Considering the differences between the two methods, the correlation of transmissibilities is much closer than would be expected and cannot be considered co-incidental. The plots on which Masch and Denny (Figure 4, op. cit.) derived their predictive curves are based on relatively few (12) although widely scattered samples and the authors do also note that the trends shown

TABLE 15

Site J(C1-95) Summary of aquifer pumping test results

WELL	T m^2/day	S x 10^{-3}	ANALYSIS
WW East	723	1.15	Leaky artesian r/B = 0.2
WW Central	835	2. 5	Leaky artesian r/B 0.2
Average	784	1. 8	

TABLE 16

Comparison of grain size and aquifer pumping test transmissibilities

1.	2.	3.	4.	5.
JA	1743	481	-72%[⊠]	1
JB	616	498	-19%	2
JC	1541	866	-44%[⊠]	3
JD	867	858	- 1%	4
JE	611	623	+ 2%	5
JF	587	560	- 5%	6
J(KK1-12)	1054	608	-42%	7
J(F1-97)	841	665	-21%	8
J(A1-LP3C)	250	298	+19%	9
J(C1-95)	784	653	-17%	10

⊠ Pumping Test value clearly erroneous

Columns:-

1. Well site
2. Transmissibility in m²/day based on pumping test analysis
3. Transmissibility in m²/day based on grain size analysis
4. Percentage change in 3 from 2
5. Sample number in Text Figure 7.

TABLE 17

Comparison of transmissibility (model and aquifer test values) in Phase 1 Area

1	2	3	4
JA	846	810	-[x]
JB	756	765	883[x]
JC	1046	866	-[x]
JD	911	968	976[x]
JE	580	732	744[x]
JF	641	933	960[x]
J(KK1-12)	869	1171	1617[x]
J(F1-97)	950	1245	1421[x]
J(A1-LP3C)	400	683	731[o]
J(C1-95)	1200	1182	1313[⊠]

Columns:-

1 Well site
2 Model transmissibility in m²/day
3 Aquifer transmissibility in m²/day based on grain size analysis
4 Aquifer transmissibility based on pumping test values for responding intervals combined with grain size analysis for non-responding interval. Values at JA and JC not included.

x PMM aquifer
o LMM aquifer (upper levels)
⊠ Both aquifers

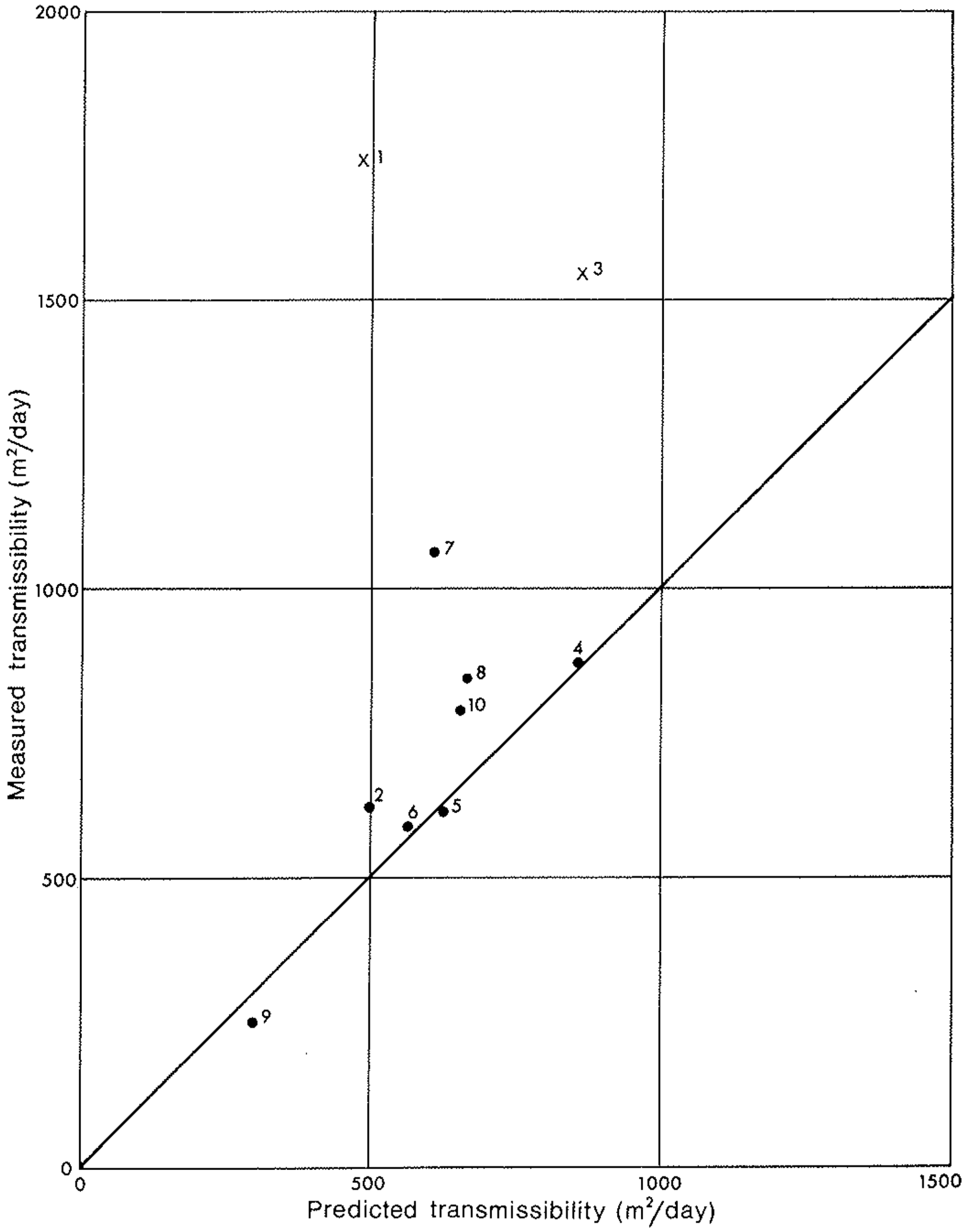


Figure 7. Plot of predicted transmissibilities (m^2/day) based on grain size analyses versus measured transmissibilities based on pumping test analyses (x pumping test analyses known to be erroneous; sample numbers from Table 16 of this report)

are in close agreement with the findings of other authors. The application of the predictives curves to 8 field samples do not however provide a very close confirmation. Listed below in column (a) are percentage differences between the predicted in relation to measured values, and derived by measurements made on Figure 10 (op. cit.)

Sample	(a)
1	+127%
2	+96%
3	+14%
4	+30%
5	+ 4%
6	+ 5%
8	- 20%

The field samples were reconstituted 10 feet intervals obtained by power auger using drilling mud. Permeability was measured by laboratory permeameter. Several possible explanations for the differences between measured and predictive values may be postulated but unfortunately the authors do not provide data on which a preference could be made. Despite this poor confirmation provided by the authors, it is considered that the correlation provided by the Phase 1 results indicates that in this particular environment, i.e. the PMM aquifer in the Phase 1 Area, the predictive method is applicable and can provide values of field transmissibility, probably within 20% accuracy. Further confirmation of this correlation is required and it is hoped can be obtained during subsequent well field development.

The correlation also provides other important indications. It confirms the general absence of cementation and dispersed clay material and also suggests that the horizontal and vertical permeabilities within the sand sections are likely to be of the same order, a factor which is of significance in assessing the validity of the model construction. Since the pumping test effectively measures the response of a relatively large section of the aquifer, the correlation indicates overall homogeneity of this section.

Average permeability values (Table 4) fall within a relatively narrow range. Variations in detail are shown by the individual site results but on the whole the variations are not of a large order. (see Figure 6 for example). The restricted range and median values of permeability correspond more closely with the parameters for eolian deposits (see abstracted data from Davis 1969 below) although other evidence indicates a fluviatile origin. The characteristic possibly relates to the derivation of these sands from older Nubian and Palaeozoic rocks.

	Darcys	
	Range	Median
1. Coarse channel deposits	1-200	50
2. Channel deposits, ephemeral streams	0.1-100	5
3. Eolian deposits	5-50	25
4. Phase 1 average values	11-28	17

(Data in 1-3 above from Davis 1969).

2.2.4.2. Vertical permeability of the semi-confining clay layers.

Values determined from leaky artesian analysis occur in the main range between 0.0015/0.0084 m/day with two extreme values of 0.0007 m/day. Davis (1969) quoting Tanaka and Hollwell refers to silts and clays composing overbank deposits on broad floodplains having permeabilities in the range 10^{-3} to 10^{-1} darcy (0.008 7/0.087 m/day. Evidence has been provided to indicate such an origin for the PMM clay material and the calculated permeabilities are therefore consistent.

2.2.4.3. Specific yield

The analyses of the upper 30 feet at each of 9 test drilling sites plotted on the Klein(1967) diagram (Figure 8) all show a specific yield in excess of 30%. There is a general correlation of the plotted positions with the equivalent permeability values (based on the Masch and Denny method) i.e. higher specific yield corresponding with higher permeability. The resolution of the permeability contours in the Klein diagram is small but there are some obvious discrepancies with the Mash and Denny results which may indicate differences in significant sedimentary characteristics in the two environments. The Libyan sediments are clean and generally composed of well rounded sand grains, both features which would tend towards an increase in specific yield. It would seem reasonable to infer that the specific yield will occur most probably in the range 25-35%. Despite these indications, it was considered advisable to utilise a conservative range (10-15%) in the model studies but the likelihood of the higher range must be borne in mind.

2.2.4.4. Recommendations for aquifer pumping tests.

In carrying out aquifer tests in this type of lithological sequence the following recommendations are made:

(i) It is important to define lithological boundary conditions during drilling and to place the screens in production and observation wells accordingly.

(ii) Well screens of observation wells can be set centrally in a uniform aquifer without clay layers; with significant clay layers, it is preferable to set screens straddling the layers, but particularly so if the aquifer shows significant variation of permeability with depth, since subsequent head variations in a vertical section can give misleading results.

(iii) The value is emphasized of flow velocity logs in the production well to assist design criteria as well as for analytical purposes.

(iv) Slug tests should be carried out on all observation wells to ensure good hydraulic continuity. They can also be carried out on production wells as a check on aquifer test results. Very precise measurements and techniques will be required for the latter test.

(v) A pre-test evaluation should be carried out in order to determine observation well locations so that a comprehensive set of positions on the type curve can be obtained. The evaluation can utilise grain size transmissibility and lithological data to determine probable boardary conditions.

(vi) Specific yield can best be determined using long term abstraction data in combination with suitably placed observation wells with screens open at the water table. Nuclear logging would assist in evaluation delayed yield effects. A correlation with grain size analysis should be attempted as the advantages of such a correlation will be great.

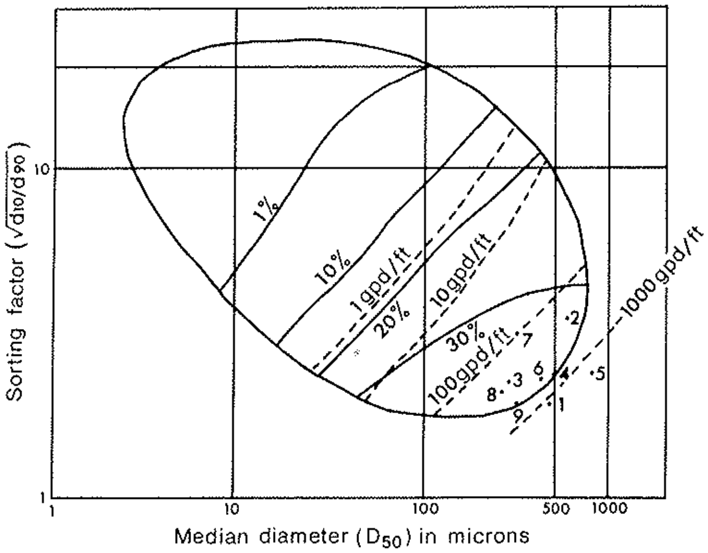


Figure 8. Relation between textural features and hydrologic properties (basic diagram after Klein, 1967. Percentage values are of specific yield. Sample numbers from Table 5 of this report)

2.3. Regional groundwater flow patterns

A general discussion of groundwater flow patterns was given in the Interim Report, based largely on the piezometric surfaces map of the PMM and LMM aquifers. In consequence of improved knowledge of the stratigraphy, a revised version of the piezometric surfaces is presented with this report (Map Figure 6.). The intersections of the piezometric surfaces are also shown on the geological cross-sections. (Map Figures 1-4).

To the north of latitude 29°00' the saturated thickness of the PMM reduces rapidly and wedges out altogether at some distance to the east of the PMM outcrop boundary. At J[A1-LP 3C] on latitude 29°06' north and longitude 20°32' east for example the water table occurs at the base of the redefined PMM. Piezometric contours in the PMM in the northern Phase 1 Area are not shown in Map Figure 6 although they are likely to be generally co-incident with those in the LMM. Three wells to the north of 29°10' are accessible to the PMM and recorded piezometric levels show general conformity with the LMM surface. At C1-95 the Company water wells are screened in the PMM whereas J[C1-95] A is within the LMM but all well water levels are co-incident. Thus the two aquifers are more or less continuous in the northern Phase 1 Area with no head differential. The PMM aquifer is mostly of unconsolidated sands. The LMM is more variable but has a significant sand percentage in its upper levels.

To the south of 29° 00' latitude, the piezometric contours of the PMM aquifer are generally as shown in the original version with an approximate east-west strike and northerly gradient. On the assumption that the contours are coincident with those of the LMM to the north of 29° 00', the gradient is maintained at about the same degree or perhaps initially somewhat steeper in the central area. This may seem a little surprising in view of the reducing thickness of the PMM for there seems unlikely to be a sufficient compensatory increase in transmissibility. Interaction with the LMM could supply a possible explanation, for the piezometric surfaces converge rapidly and become virtually identical the north of 29° 05'. There is also a lithological convergence with increasing sand percentage in the shallow LMM.

Flow patterns in the shallow LMM aquifer are more complex and in the central Phase 1 Area below the PMM aquifer, more uncertain. The contours are approximately co-incident with those of the PMM in the far south near the Calanscio oil field and here again the two aquifers are virtually continuous and there is a high percentage of sand in both the PMM and shallow LMM.

The diverging trends in the water levels in the LMM aquifer in the western Phase 1 should be noted. To the north-west of Ain Zubairi there is a marked gradient towards the sabkhat Hutaytat Al Fawziyah where discharge by evaporation is occurring. There is also a marked flow gradient to the north east of Ain Zubairi and considered in the context of the piezometric differentials in the two aquifers, the feature could indicate upward leakage into the PMM. Confirmation is not provided by the piezometric levels in the PMM in this area, nor by geochemical trends, although information on both aspects is limited.

An alternative explanation is a marked reduction in transmissibility of the shallow LMM in the area showing a steep hydraulic gradient, but until further information becomes available, both concepts, i.e. leakage or reduced transmissibility, must be considered possible.

In the central Phase 1 Area, the flow lines show a curving trend from the LMM/PMM boundary firstly north eastwards and subsequently northwards.

Over much of the central and south-eastern Phase 1 Area, a head difference occurs between the piezometric surfaces of the confined LMM and unconfined PMM, but whether upward leakage from one to the other occurs depends on the permeability of the boundary horizons. General qualitative indications can be deduced from the geological cross sections (Map Figures 1-4) which also show the intersections of the piezometric surfaces. Areas where leakage is most probable is in the southern Phase 1 and in the area to the north-east and east of Ain Zubairi and discussed above. In the southern Phase 1 Area, some confirmation of upward leakage is provided by the bending of the PMM contours to the north of the Calanscio Oil Field. In the central Phase 1 Area, although differentials exist, the boundary horizons contain a significant percentage of clay with consequent impedance to upward flow.

Some discharge by evapotranspiration is presumably occurring in the vicinity of Augila and Jalu oases (see section 2.4.7.6) and possibly near the northern border of the Phase 1 Area where the water table is shallow. Some curvature of the water table contours may perhaps relate to this process. However, surface vegetation appears limited and the main sabkhats occur north of the Phase 1 boundary.

2. 4. Hydrogeochemistry

2. 4. 1. Objectives

A comprehensive geochemical investigation of the groundwaters in the Phase 1 area was made during the period July 1971 - August 1973. The initial findings of this investigation have already been reported (Wright et al 1973). Previous investigations of groundwater in this area have been limited but reports by Van Everdingen (1962). Jones (1963, 1964, and 1971) refer to the water quality. Detailed water quality investigations of the area were included in the regional survey of Cyrenaica by IGS, the results of which have been reported by Wright and Edmunds (1969 and 1971). The present geochemical report summarises knowledge of the area up to date, and in addition to results on major element chemistry, also includes data on trace element and isotope geochemistry (hydrogen, oxygen and carbon isotopes). This comprehensive treatment of the groundwater geochemistry provides a means of understanding of the evolution of the aquifers, as well as providing the necessary information on water quality.

The objectives therefore are:

(1) To determine the three-dimensional water quality distribution in the Post-Middle Miocene (PMM) and Lower and Middle Miocene(LMM)aquifers.

(2) To identify the main hydrogeochemical units, relate these to the hydrology and the geology as reported in other parts of the report, and thence to establish the relationships between the units.

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

(4) To determine the likely age of the groundwater, stratification and the recharge history of the aquifer, and to compare these data with adjacent areas in Libya.

2. 4. 2. Methods of Study

2. 4. 2. 1. Sampling

Details of sampling were given in the Interim Report.

2. 4. 2. 2. Analysis

Full details of analytical methods used have been covered in the Interim Report. In addition to stable isotope analyses carried out at IGS, further analyses were carried out by Isotopes Inc. (USA)

2. 4. 3. Three Dimensional water quality distribution

The Phase 1 area is centred on a north-trending freshwater lobe, the approximate boundaries of which were proved in earlier studies. This lobe is bounded on the east, north, and west by zones of inferior water.

2. 4. 3. 1. Total mineralization

The water quality distribution in the area has been defined in terms of the total mineralization in the Interim Report (Map Figure 11). Separate contours were drawn for PMM and LMM aquifers; however the stratigraphic designation is now no longer correct in detail on account of the stratigraphic revision (see section 2. 1.). Although the map defines the main water quality zones, caution is required in its interpretation, since it is a two dimensional representation of a three dimensional pattern. The more detailed treatment in this Report should clarify some of the anomalies.

There may be an error in some of the values as a result of sampling problems. Where it was only possible to depth-sample within well casings, deterioration in the water may have occurred. Water in the casing, representing that last pumped at the time of wildcat drilling, might be out of equilibrium with its initial location in the aquifer and CO_2 loss could have occurred with a concomitant bicarbonate decrease. Sulphate reduction may also have taken place if micro-organisms and organic matter had been introduced during well development. The deterioration in water quality due to storage in casings probably affects only a small proportion of the depth sampled wells. The water columns in all depth sampled wells were logged with electrical conductivity probes prior to sampling, and in nearly all cases, there was no apparent quality change with depth. However, the problem was only highlighted relatively late in the investigation when wells sampled in Concession 103 gave apparently much lower conductivity values than adjacent pumped wells, tested during the development; this can be appreciated by comparing individual values in Map Figure 11 of the Interim Report (e. g. JA and 01-103). It is noted, however, that several depth sampled wells, for example N1-103, are little affected. The loss in total dissolved solids probably amounts to between 200 and 400 mg/l in the affected wells, mainly by loss of SO_4^{2-} and HCO_3^-. The geochemical interpretation in this report takes account of these anomolies.

The fresh water lobe in the Phase 1 area is defined by the 2000 mg/l total mineralization contour which is used as the limit of potability in this report (Map Figure 11 of the Interim Report). There is an overall quality change from the south of the area (1000 mg/l to 2000 mg/l) over a distance of some 130 km, which represents a very gradual regional change. The lobe occurs within the re-defined PMM aquifer and the total mineralization in this aquifer which thins northwards is not known but may be reasonably low. The rapid quality deterioration in the flow direction north of 29°20' N is an expression only of changes occurring within the LMM aquifer. To the east, however, the quality deterioration is found both in the LMM and PMM aquifers. The control of this quality change is different in both aquifers and is discussed in the following sections. The water quality in the LMM deteriorates westwards from 1000 to 3000 mg/l at an acute angle to the groundwater flow, and thus suggests that the control must be geological. The total mineralization in waters beneath the area of the Miocene outcrop on the west of the lobe, however, is very similar to that in adjacent wells in the PMM aquifer, and the junction between water in the two aquifers is therefore not clearly marked.

2. 4. 3. 2. Chloride

The regional geochemical variations shown by chloride are important hydrogeologically since they tend to reflect differences in flow patterns, flushing or evapotranspiration effects rather than chemical reactions (other than solution) that may have occurred in the aquifer. Chloride is relatively inert and has not been affected by reactions in well casings. In this report the chloride variations are used as an indicator of changing physical or geological controls on the water quality and in this respect is more significant than the total mineralization map.

Chloride distribution in both aquifers is shown in Map Figure 7. In the main Phase 1 development area chloride values are relatively constant between 350 and 450 mg/l increasing to 780 mg/l in the north of the PMM aquifer. Values in the LMM aquifer in the extreme south are rather low (230 mg/l), but adjacent groundwaters in the lower aquifer in general have the same chloride values as in the PMM aquifer. A sudden increase in chloride is found in the LMM aquifer in the north and north-east (> 2000 mg/l Cl). The chloride variation emphasises the significant quality variations to the east of the freshwater lobe within the PMM aquifer. These patterns are discussed geochemically below, but three features should be noted at this stage - the local deterioration around Augila and Jalu, the broad area of poor quality water east of Gialo oilfield and the band of very low chloride groundwater to the west of Aquitaine 'A' oilfield which contrasts markedly with that in adjacent areas.

2. 4. 3. 3. Sulphate concentration and Sulphate/Chloride ratios

Sulphate distribution is shown in two ways in Map Figure 8, as individual values, and as the SO_4/Cl ratios plotted as symbols; the isochlor from Figure 7 is also plotted for reference and values from the PMM and LMM aquifers are distinguished. The following points are noted:

1) Sulphate values in the PMM freshwater lobe are typically 400 ± 200 mg/l and SO_4/Cl ratios are generally near 1.0.

2) High sulphate values (>1000 mg/l) are restricted to the northern half of the map area. The principal areas of high sulphate in the LMM correlate with the marine facies of the LMM aquifer in the north west and north east; high SO_4 also occurs locally in the PMM and to the north of Jalu.

3) LMM groundwater confined beneath the PMM does not appear to be more enriched in SO_4 than in the overlying aquifer except in areas to the north suggesting that the control of SO_4 is related to the marine/continental boundary in this aquifer (see Section 2. 1.).

4) The northern sector of the LMM aquifer is the only area in which an increase in SO_4/Cl ratio accompanies the deterioration in total mineralization, indicating that this is related to solution of gypsum/anhydrite, elsewhere the SO_4/Cl ratio remains relatively constant along the flow direction, denoting a constant aquifer mineralogy.

5) A geochemically distinct zone in the south of Concession 97 can be identified

on the basis of SO_4/Cl ratios. In this area where an increase in total mineralization and chloride have been noted, low SO_4/Cl ratios and relatively low SO_4 values are found. This zone contrasts therefore with the freshwater lobe to the west, although the absolute SO_4 values are similar (<600 mg/l). A possible explanation of this feature could be the existence locally of sebkha deposits with chloride mineralization within the PMM aquifer.

2. 4. 3. 4. Magnesium/Calcium ratios

Magnesium/Calcium ratios are tabulated in Appendix 12 of the Interim Report and are illustrated in Text Figure 9. One feature of the Mg/Ca ratios is that the highest values usually occur in the least mineralised groundwaters, for example in the southern PMM aquifer and hence most of the increase in mineralisation should relate to an uptake from low Mg/Ca sources within the aquifer. In general, however, the Mg/Ca ratios remain fairly constant throughout the PMM aquifer and this remains so within the more saline groundwater east of Gialo oilfield and around the Jalu district; an increase in total mineralization, therefore, is accompanied by Ca and Mg uptake in ratios similar to those already existing in the groundwater.

Whilst groundwaters in the PMM seldom have Mg/Ca ratios above 1. 0, in the LMM a greater variability is found, particularly in the western area. High ratios are found in the non-marine areas of the LMM in the south but relatively low ratios characterize the marine facies in the north; this contrasts with the strontium results described below (4. 5. 2) and it may be possible to use the Mg/Ca ratio to distinguish LMM from PMM groundwaters.

2. 4. 3. 5. Water quality changes with depth

The regional water quality map (Map Figure 11 (Interim Report) and Map Figure 7 of the present report) do not take into account the three dimensional water quality variation, and six representative sections (Map Figure 9) have been drawn to illustrate the probable water quality changes with depth, based on chloride data; lines of section are shown in Figure 7.

Nearly all water supply wells drilled during hydrocarbon exploration were less than 300 metres deep, many less than 150 metres; in some areas, for example Concessions 103, 59, and 51, water from deeper levels is exploited. The six sections illustrate various features of the quality variation with depth as follows:

(1) The relationship between the thin, saturated thickness of PMM aquifer in the north overlying the LMM aquifer is illustrated in sections A-A' and B-B'. Chloride values in the LMM aquifer are similar to those in the overlying PMM aquifer, although SO_4 concentrations are considerably higher in the lower aquifer. The chloride concentration increases in the east of the section where the LMM aquifer is generally not overlain by saturated PMM sediments.

(2) Water quality stratification in the central fresh water lobe of PMM aquifer (<500 mg/l chloride) is uncommon as demonstrated by specific electrical conductance logs run during the exploration programme (see Interim Report and Appendices). From the sections, no systematic relationship between quality and depth can be established by comparing adjacent well groups.

(3) A clearer relationship between the fresh and brackish water near Jalu can be seen from sections C-C' and D-D'. Poor quality water at Augila Oasis is apparently restricted to the near surface and may be underlain by relatively fresh water. The same situation probably also exists at Jalu Oasis but there are no deep boreholes in the vicinity. North of Jalu however in 102D Field there is a very clear boundary between fresh water (e. g. 1120 mg/l pumped to the camp supply) and saline water (4740 mg/l) at the same depth within a few kilometres. This boundary has been clearly defined from conductance logging of accessible wells in 102D field. It is possible that locally to the west of 102D field, a wedge of fresh water extends beneath the saline groundwater (shown tentatively in sections C-C' and D-D'), but evidence from deeper wells within the PMM aquifer to the north and east (Concession 51, and 102) show that here saline water must be widespread throughout the saturated thickness of the aquifer. This area is discussed in more detail in section 2. 4. 3. 6.

(4) Fresh water at Gatmir is a local anomaly, possibly a superimposed feature similar to that in Concession 105, although field relationships to the east and south are ill-defined.

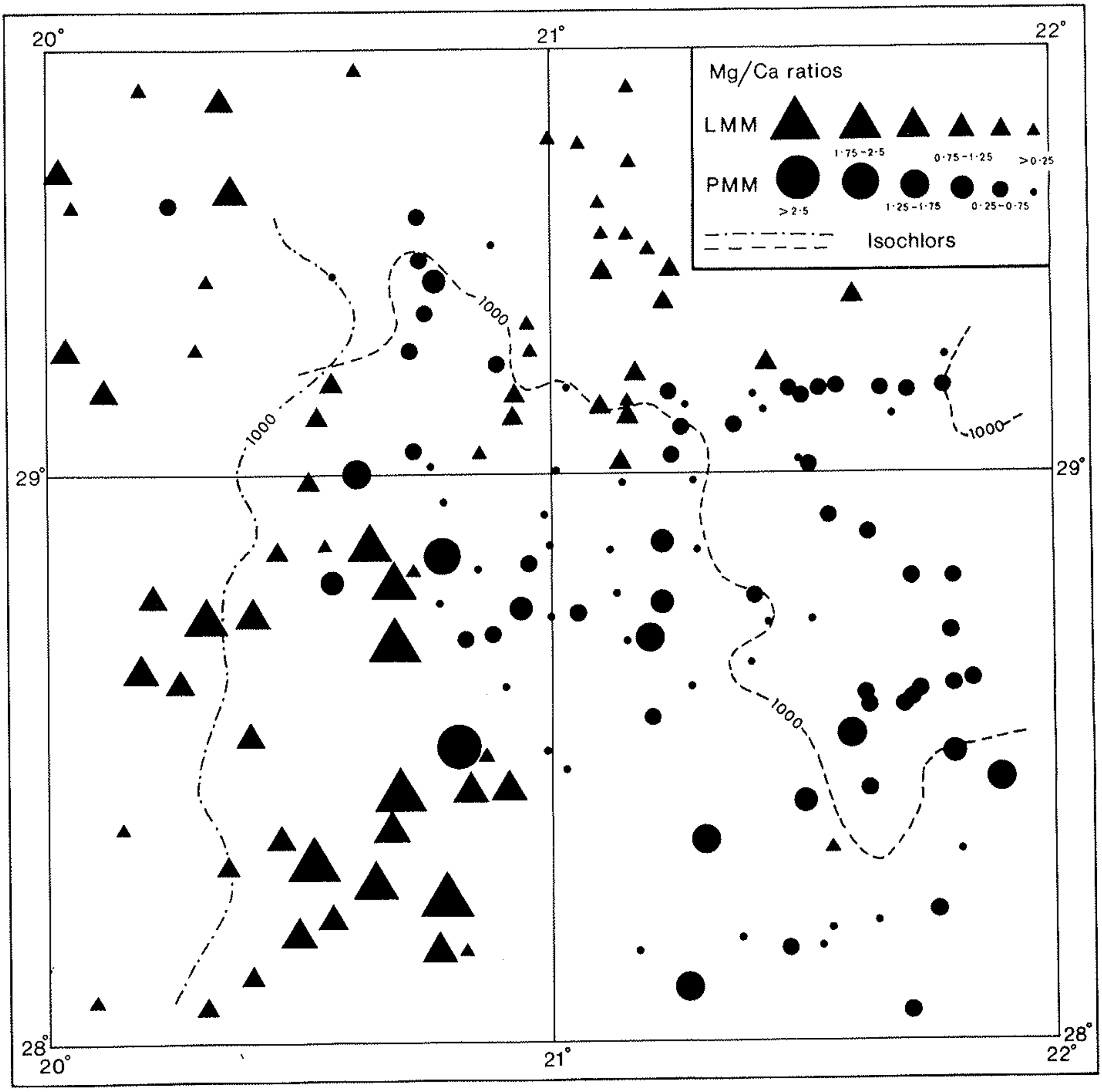


Figure 9. Mg/Ca ratios

(5) Chloride contours on section E-E' clearly define the lower limits of a fresh water zone in Concession 105. It can be seen that this is not a near surface phenomenon but extends to at least 70 m below the water table at E1-105. The boundary is steep on the east but to the west there is evidence for stratification, (B1-80, W1-80).

(6) The quality deterioration eastwards from Gialo Oilfield is probably general throughout the thickness of the PMM aquifer (section F-F').

2.4.3.6. Local quality changes around Jalu

A detailed sketch map of the groundwater quality in the PMM aquifer around Jalu is shown in Figure 10. This map is based mainly on an intensive sampling and chloride analyses of samples from 102-D field and supplemented by traverses through Jalu oasis where specific electrical conductance only was measured.

The chloride contours define the very sharp boundary of the fresh water on the west (c.f. section C-C', Map Figure 9). The saline water appears to be localised immediately to the north of Jalu oasis and a sharp divide is also apparent within the Oasis itself. Deterioration is in the direction of flow from south to north and it is possible from the spatial arrangement that this saline zone is directly related to evapotranspiration, plus human activity within the oasis area. If this is the correct explanation, then fresher groundwater could be encountered by drilling deeper wells to the base of the PMM within the oasis itself.

Calculations based on the length of the saline zone to the north of Jalu and the permeability and hydraulic gradient, confirm the supposed origin - that the saline zone could be the northwards migration of saline water from the oasis. A period of 4000-5000 years would be required for the dispersion of this saline water; this is consistent with the existence of younger water near the surface which is found in the vicinity of Aquitaine 'A' field and at Jalu (Section 2.4.7.3.1.). This theory would presuppose that at that time the water levels in Jalu oasis were raised to ground level and that saline layering was developed at that time in the oasis deposits. This feature seems consistent with age and hydraulic factors.

2.4.3.7. Deep groundwaters in the Lower Miocene/Oligocene

In these areas, 103-A, 103-D and Gialo 59-E groundwaters in the Oligocene and deeper Miocene have been developed for oilfield uses and although a detailed study is beyond the scope of this report their existence is noted, since some are of reasonable quality. A representative set of analyses is given in Table 18 and further details of these waters is also given in Appendix 12 of the Interim Report.

The total mineralization of those waters quoted ranges from 5000-7800 mg/l; field survey of existing wells (see Table 5, Interim Report) has indicated that there is a range in specific electrical conductances in pumping deep wells from 5250 to 18250/ µmhos. Their dominant composition is (Ca, Na) SO4 and it is possible that in favourable circumstances these waters may be suitable for limited agricultural use.

Field chemical parameters were determined on two of these wells (W36-103A and W52-103D) and the results given in Table 19. Problems for development include the high formation temperature (around 47.0° C) and the low e H, and these groundwaters have given serious corrosion problems in wells lined with mild steel in 103A and 103D Fields.

2.4.4. Geochemical relationships between groundwaters in Phase 1 Area

Regional distribution maps and water quality sections indicate the extent of fresh and saline water over the Phase 1 area. To provide a clearer indication of how these waters are interrelated it is necessary to consider the geochemistry of waters, particularly with regard to the major ionic constituents. The geochemistry of the fresh groundwater in the central Phase 1 area is compared with the surrounding poorer quality water in the PMM aquifer as well as in the Lower and Middle Miocene.

2.4.4.1. Geochemistry of the central fresh water lobe (PMM)

All groundwaters pumped from the PMM aquifer in the fresh water lobe (<2000 mg/l) fall in a restricted field on the trilinear diagram (Figure 11). Detailed analyses of individual sources can be found either in the well completion reports (Interim Report Appendix 1-11) or in the tabulation of chemical results (Interim Report Appendix 12).

The uniformity in composition over the extensive area of fresh water as far north as J(C1-95) and throughout the saturated thickness of the PMM is evidence of the large scale homogen-

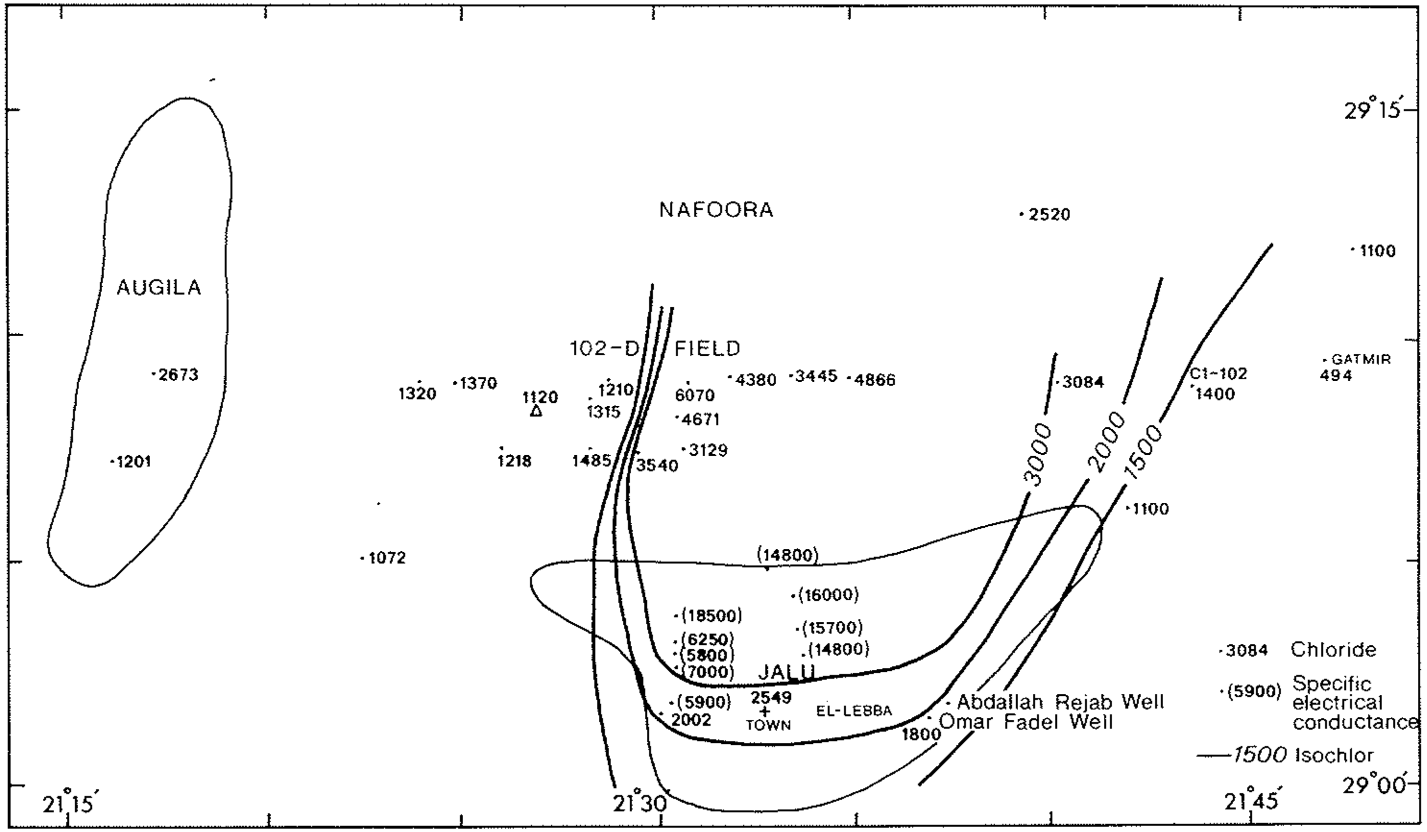


Figure 10. Sketch map of water quality variations around Jalu Oasis

TABLE 18

Chemical analyses of representative groundwaters from the deep Miocene/Oligocene of the Phase 1 development area - Occidental Fields 103-A, 103-D and Oasis 'Gialo' 59E Field

	IGS No.	Well Depth(m)	Sample Depth(m)	Ca	Mg	Na	K	HCO_3 mg/l	SO_4	Cl	Sr	Total Solids
103-A Field WSW-36 (4/72)	72/270	899	721	489	132	950	71	173	2779	621	8.8	5224
WSW-2	73/139	898	810	530	130	2050	63	104	3300	1640	8.1	7817
WSW-21	73/140	891	810	510	140	1040	70	138	2800	640	8.0	5338
WSW-36 (12/72)	73/141	886	721	533	132	874	63	129	2730	588	8.5	5049
WSW-23	73/142	897	861	520	134	2020	85	138	3460	1710	7.9	8067
WSW-4	73/143	898	-	530	144	1047	69	137	2990	806	7.9	5731
103-D Field W51-103D	72/265	908	670	472	117	1230	61	137	3215	756	7.0	6004
W16-103D	72/607	1000	996	542	117	1300	61	140	3398	941	10.0	6499
Gialo 59E W38-59	72/291	594	558	560	144	865	64	126	2610	830	7.9	5199
W37-59	72/583	637	593	644	159	1460	95	116	2754	2140	12.9	7368
W230-59	72/589	598	544	596	137	990	74	111	2580	1290	12.2	5778

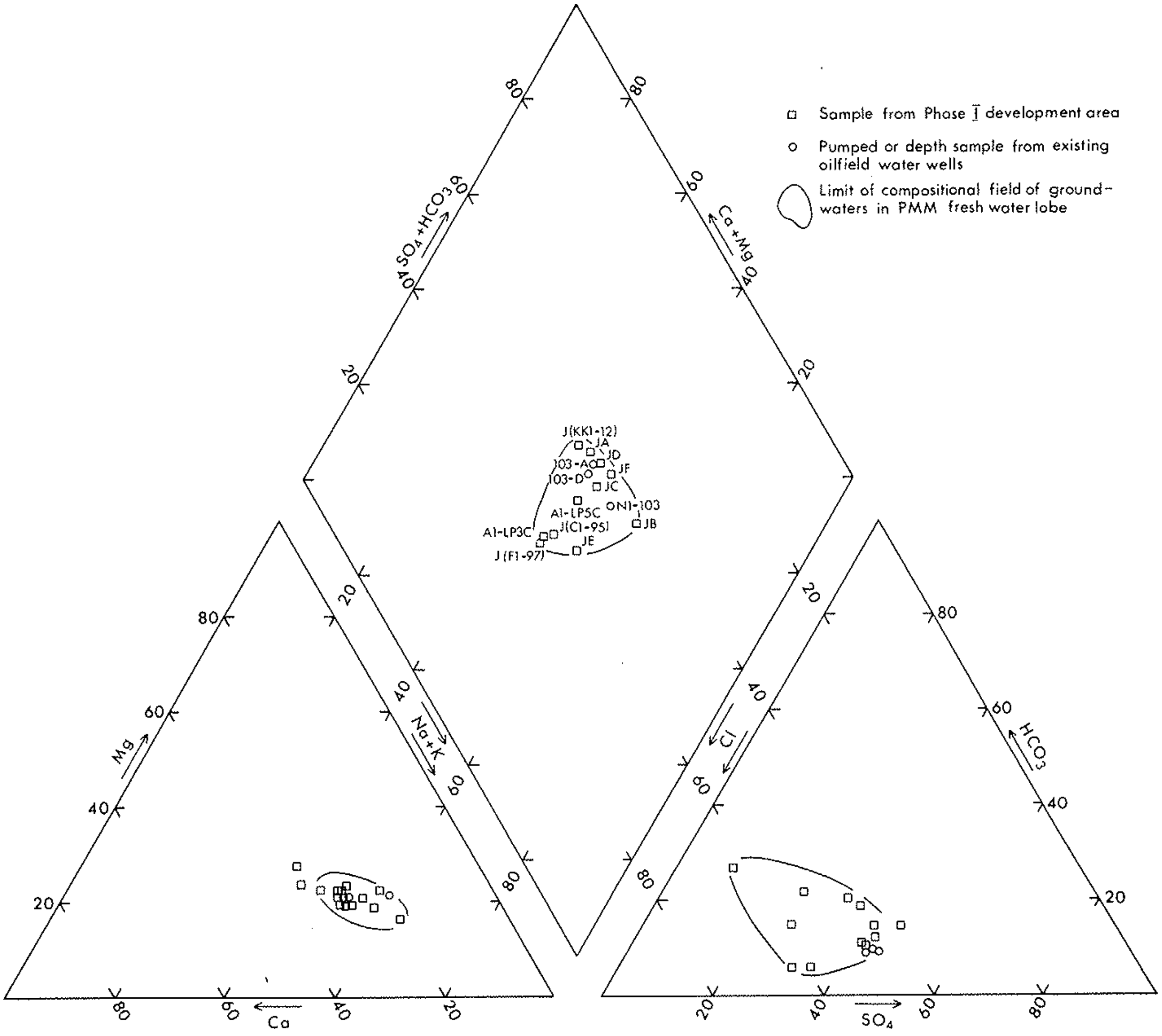


Figure 11. Geochemistry of groundwaters in the central fresh water lobe (PMM)

ity of the aquifer, and suggests that the clay horizons do not isolate pockets of stagnant water. The uptake of soluble constituents is apparently from a constant source throughout the area. The mixed ionic composition is maintained from south to north through the aquifer and it is clear that selective sulphate uptake does not occur. The composition is consistent with the sedimentological evidence which suggests that the PMM, aquifer is composed of a sequence of alluvial plain deposits and that there is an absence of any marine influence.

2. 4. 4. 2. Relationship between groundwater in the central fresh water lobe and in the area south and east of Gialo oilfield Field (Concessions 97, 80, 105).

The fresh water lobe extends south of Gialo Oilfield and includes the very distinct fresh water zone extending just west of A1-105. This zone is elongated from north to south (approximately in the direction of groundwater flow) and must extend beyond the boundaries of the Phase 1 area. The quality deteriorates sharply to the north and also to the east within this small area (Map Figure 7).

The geochemistry of representative waters is shown in Figure 12; all these are pumped samples or reliable depth samples. A link with the main fresh waters is provided by sample DDDD1-59 which plots within the same compositional field and indicates that the PMM groundwaters are uniform in their chemistry along the line from DDDD1-59 to J(C1-95) and differ only in total mineralization. Eastwards, across the flow direction (02, 03-80) water of the same total mineralization changes towards a composition dominated Cl rather than $Cl+SO_4$, the Ca and Mg remaining constant. Continuing eastwards, the narrow zone of fresh water is reached in which HCO_3 is the dominant anion e. g. B1-80; these groundwaters fall in a distinct field on the trilinear plot.

The boundary of the main homogenous geochemical unit which includes the centre Phase 1 area is found therefore at around 21° 30'E and to the east of this line the geochemistry is more complex, although the composition still remains similar on moving along a flow direction.

The main compositional change, a decrease in the SO_4/Cl ratio is found, moving from Wells 02, 03-80 (Figure 12) northwards along the flow direction towards A1-97, and this suggests a lithological control of the quality deterioration in this region, producing a (Ca, Mg) Cl groundwater. This could be brought about by an increase in fine grained sediments although no lithological change has been found from examination of the formation logs. Saline silts associated with evaporating flood water in a former river basin for example might have produced the observed change in groundwater composition. An alternative but less likely explanation is that local leakage from the LMM has occurred although the composition is unlike water found elsewhere in the Miocene.

2. 4. 4. 3. Geochemistry of the saline water around Jalu Oasis

The Jalu Oasis is immediately down gradient of the area of (Ca, Mg) Cl groundwaters described in 4. 2, and it can be seen that around Jalu (e. g. G1-97) this general chloride dominant composition is maintained (Figure 13), and that waters with ionic composition similar to the main fresh water lobe do not occur. Transitional waters between the two groups are found, however at F1-97 and 102-D camp. There is a very slight increase in sulphate as the water moves north and becomes more saline as shown by the regional map and the difference between the two fields in Figure 13. This SO_4 shift is not very significant, however, in view of the doubling or trebling of the total mineralization. It is important to note that the increase of total mineralization is virtually isochemical. This strongly suggests that the deterioration is the result of <u>in situ</u> concentration by evapotranspiration and/or by dissolution by the groundwater of residual soluble salts, possibly during fluctuation in the water table. This is supported by the fact that shallow wells in Jalu follow the same trends as waters outside the oasis. Saline groundwater from pumping wells in Concession 51, perforated at 50m below the water table, have the same composition (e. g.GOSP3-51), as the near surface depth samples (e. g. GOSP3-51). Water in the LMM beneath this area is rather less saline although having higher SO_4/Cl ratios than overlying water; the chemical composition of this water however, as can be seen in Figure 13, does not support upward leakage of LMM water as an explanation of increased salinity (see also section 2. 4. 3. 6).

2. 4. 4. 4. Geochemistry of groundwater to the north and west of Jalu

In the area around Augila Oasis wells have been developed in both PMM and Miocene aquifers and chemical samples from these are distinguished in Figure 14.

In the area of Augila oasis the regional flow direction is approximately N20° E and ground water flowing into the oasis area from the southeast (EE1-12) is concentrated without any significant ionic change. This saline groundwater

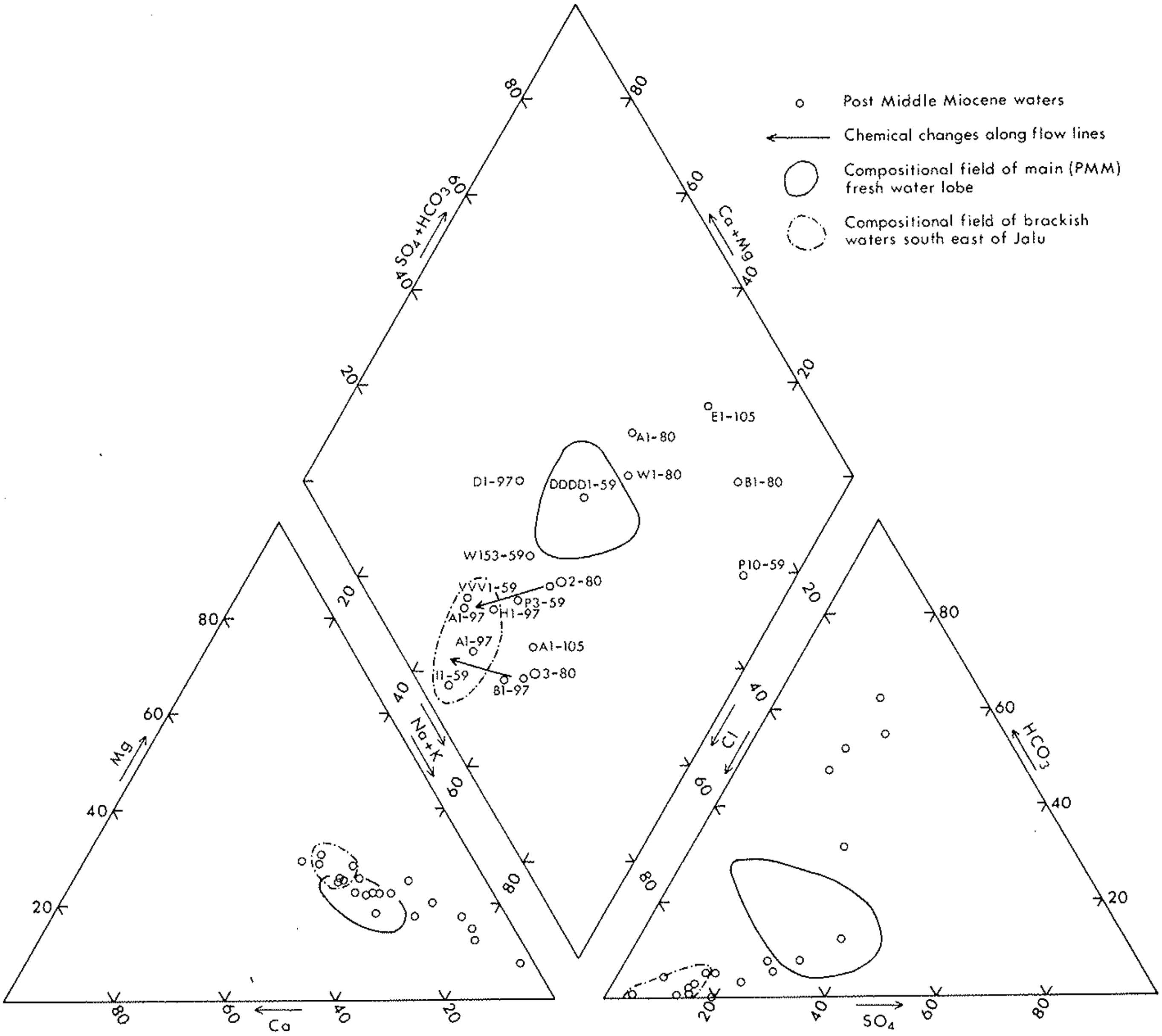


Figure 12. Relationship between groundwaters in the central fresh water lobe and the area south and east of Gialo oilfield

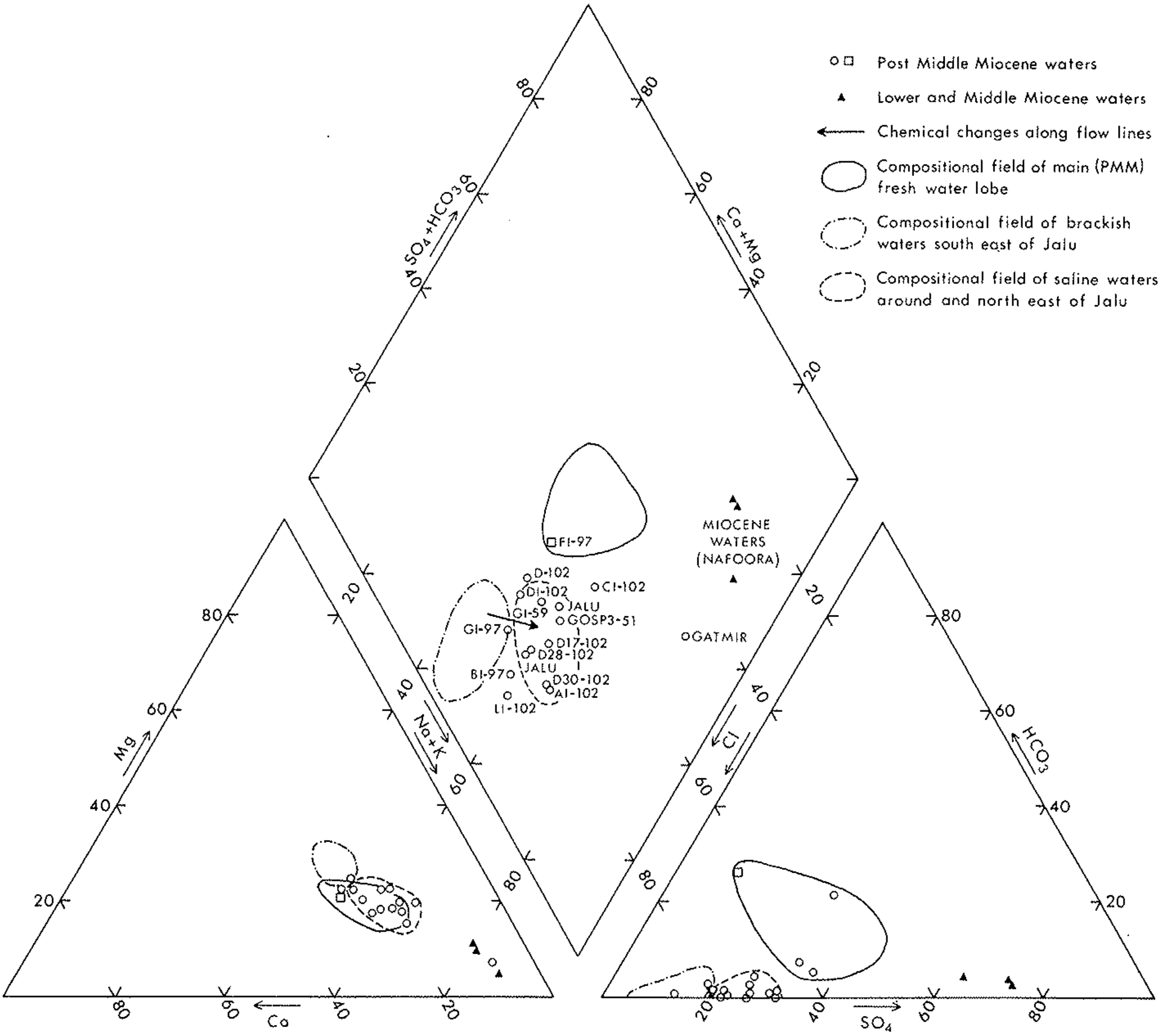


Figure 13. Geochemistry of the saline groundwater around Jalu oasis

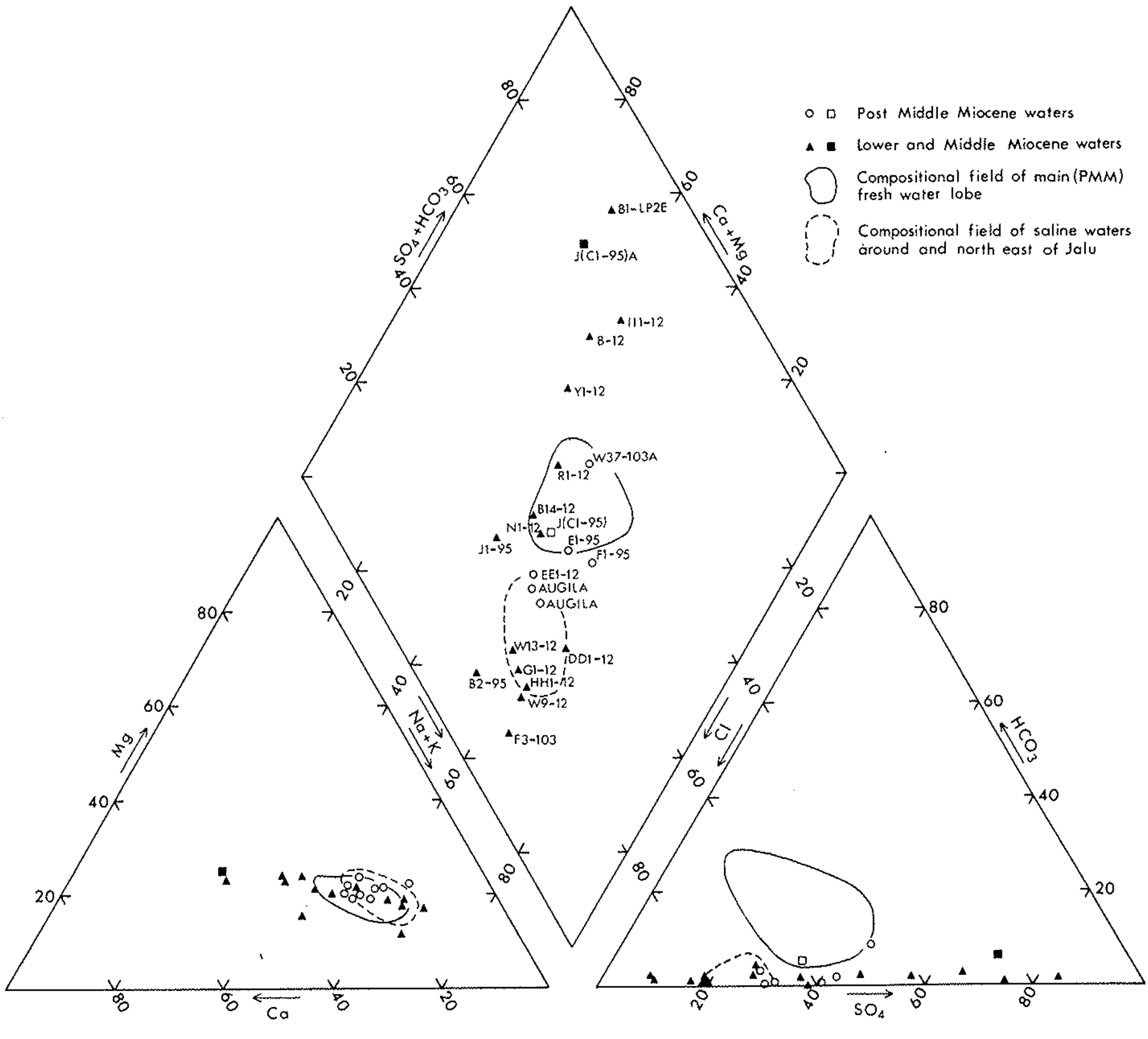


Figure 14. Geochemistry of groundwater to the north and west of Jalu

having very similar ionic composition is found in the Calanscio Formation at depth near Augila and this water may extend beneath the oasis.

North of Augila most wells are developed in the Miocene. There is a progressive increase in the total mineralization in these Miocene wells as one moves north of Augila, in comparison with the PMM groundwater. It can be seen from Figure 14 that there is a group of wells (e. g. Q1-12) having compositions dominated by Cl and Na. These compositions are still very similar to the saline waters near Jalu in the Calanscio formation. Some of the control of the chemistry of water as far north as Amal B field may be evapotranspiration from a shallow water table although the main composition is thought to be due to uptake of sulphate from the Miocene rocks. The similarity of groundwater composition locally north of Augila to water in the PMM may also indicate that there is fairly ready lateral northward flow of water from the younger into the older aquifer.

In contrast, the Miocene groundwater north west and west of Amal B field frequently contains high sulphate as is apparent from the trilinear diagram where for example B14-12, Y1-12 and J(C1-95) A contrast markedly with the water immediately north of Augila; this probably relates to the increasing importance of gypsum/anhydrite in the LMM in this direction.

The consistent composition of water in the main Calanscio fresh water lobe is again shown by this diagram (e. g. W37-103A, E1-95).

2. 4. 5. Minor and trace element occurrence

Analyses for certain trace elements were carried out on selected waters to assess any possible risk of toxicity (or deficiency) if the waters were used for human or animal consumption or for agricultural use. In addition, analysis of trace elements can provide additional information on groundwater origin (Edmunds 1971. 1973). Analyses have been made regionally for Sr^{2+}, NO_3^- and F^- and on selected samples in the Phase 1 fresh water area and at Jalu for Br, HPO_4, B, Fe, Mn, Cd, Co, Cu, Ni, Pb and Zn.

2. 4. 5. 1. Nitrate

In an earlier report on the area (Wright and Edmunds 1968) attention was drawn to nitrate levels which in certain areas, notably in southern and eastern parts of the area was found at high levels exceeding those recommended by the World Health Organisation (Anon 1971) for drinking water (45 mg/l NO_3); a map produced in the report showed nitrate distribution. The high nitrate levels are thought to be derived from fossil soil horizons or possibly from nitrate shales or evaporates located in south eastern Libya.

The Phase 1 area was however in an area where nitrate values were found to be relatively low and during the present investigation work was carried out to check this conclusion. Nitrate levels are shown in Figure 15. Water from pumped wells in the main fresh water lobe ranges from 26 to 71 mg/l NO_3. These values are acceptable for drinking water supply in this area but it is recommended that further monitoring is carried out in any development for public supply since the levels are relatively high.

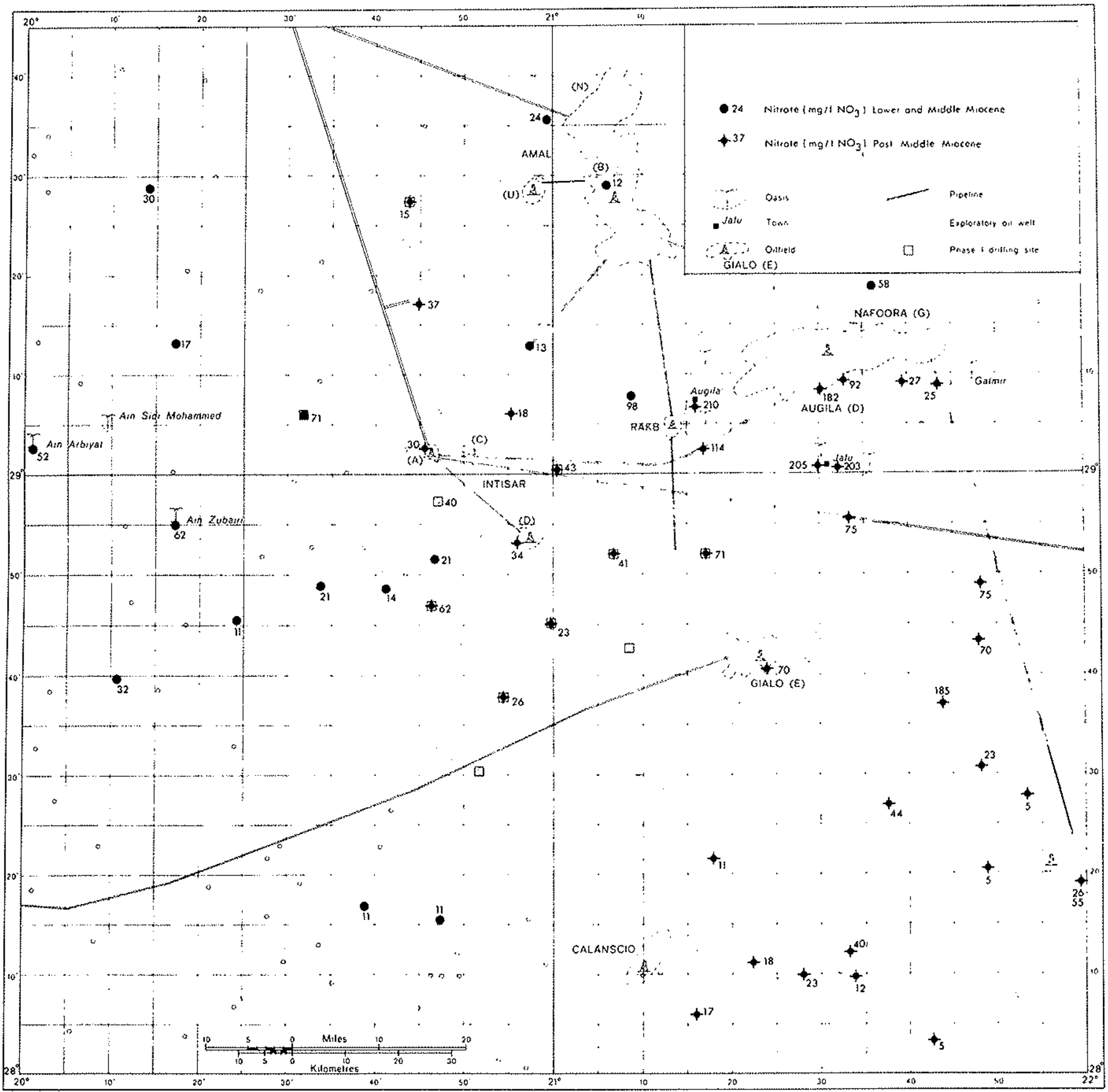
Much higher nitrate levels are found in the oasis wells at Augila and Jalu which are above WHO limits and render these sources unsafe for drinking. The high levels are here almost certainly caused by recycling of irrigation water and pollution within the oasis; these levels compare with much lower nitrate (ca. 50 mg/l NO_3) in similar waters at the undeveloped oases at Ain Zubairi and Ain Arbiyat.

2. 4. 5. 2. Strontium

Strontium was determined for reconnaissance purposes primarily to try and distinguish groundwaters from different origins especially where major elements did not show significant differences. The strontium distribution is shown in Figure 16 and results are tabulated in Appendix 12 (Interim Report).

A wide variation in Sr^{2+} is found, ranging from < 0.1 to 29 mg/l in brackish water at Ain Zubairi. In the PMM aquifer the Sr^{2+} increases rather uniformly from the south (ca 2. 5 mg/l) to around 7 mg/l in the north of the fresh water lobe and this correlates approximately with the observed increase in total mineralization. An expected increase in Sr^{2+} is also found in the Jalu area where the water becomes more mineralized. The strontium evidence would indicate again that the PMM is rather homogeneous with no marked lithofacies changes.

Much more sudden variations are however found in the Miocene. South of 28° 45'N, strontium is consistently below 2. 5 mg/l (Figure 16) whereas north of this and west of 20° 50'E there is a sudden change to values commonly in excess of 10 mg/l Sr^{2+} in an area where there is no corresponding change in total mineralization, This boundary correlates rather well with the percentage of carbonates in the Miocene (c f Map



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Jalu-Tazerbo Project - Phase I

Scale 1 500 000 Lambert Conical Orthomorphic Projection

Figure 15. Nitrate occurrence

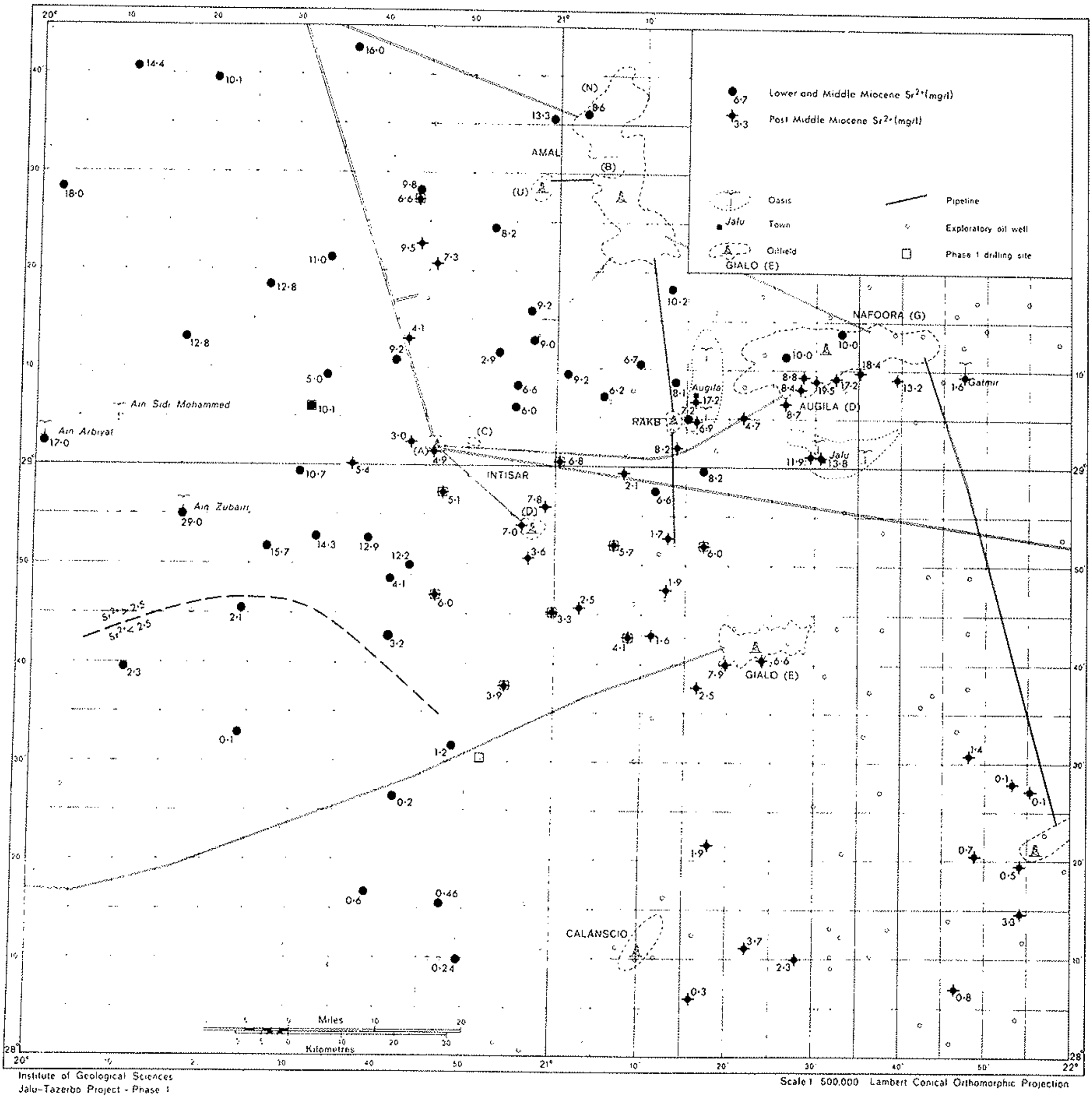

Figure 16. Strontium concentration in Lower and Middle Miocene and Post Middle Miocene Aquifers

Figure 2C Interim Report, and also the approximate line of the Miocene shoreline, (Final Report Section 2. 1.). The groundwater strontium concentration however does not seem to be so significantly high, (bearing in mind the total mineralisation in areas of evaporite occurrence (Interim Report Figure 4C) and in the area north and west of Jalu, the Sr^{2+} although higher than in the PMM groundwater is not as high as in the western Miocene waters.

The Sr^{2+} therefore appears to be a good indicator of the "marine" character of the Miocene, and is probably related to the aragonite content of the marine sediments (Kinsman 1969). In practical terms it is considered that the Sr^{2+} content could be used as one indicator to distinguish between LMM and PMM waters, especially in the west of the area where doubt may arise from consideration of other geochemical results, since the total mineralization of both aquifers in this area is almost identical.

Similarly it may be possible to use the strontium to trace a leakage of LMM water into the PMM aquifer. The sharp break in Sr^{2+} values on the central western boundary indicates the absence of connection at this point; in the south where leakage from the LMM is postulated on the basis of model studies, results are inconclusive since the concentration is similar in both aquifers.

2. 4. 5. 3. Fluoride

Fluoride results are available for a wide extent of the Phase 1 area. The results are not shown diagrammatically but are tabulated in Appendix 12 (Interim Report). Recommended (WHO) limits for fluoride in drinking water at the mean annual air temperature of the area is 0. 7 - 1. 2 mg/1 F.

The values recorded in pumped wells in the Phase 1 development area (Table 5, Appendix 12) are all at this limit or higher. Values as high as 3. 6 were recorded consistently at JA-P during the pumping test. High fluoride 2. 5 - 3. 7 mg/1 was also recorded in water from the pumping test in the Miocene at J(C1-95)A.

Although a level of 1. 0 - 1. 5 mg/1 F in groundwater is considered to be safe and indeed beneficial in preventing dental caries, values much in excess of this in cumulative doses might give rise to dental fluorosis and possibly skeletal fluorosis in children and adults. A consideration of the fluoride levels and further analysis is recommended before full scale continued use of water for public supply is considered.

2. 4. 5. 4. Boron

Boron results are available for groundwater from the pumped exploration production wells in the Phase 1 area as well as for several others and are tabulated in Appendix 12 of the Interim Report.

In the pumped samples, on which the greatest reliability is placed, the value appears fairly constant at 0. 50 $\pm$ 0. 10 mg/1 B. In the Miocene J(C1-95)A the level is higher 0. 86 mg/1 B, whilst still higher values, up to 4. 0 mg/1 B are found in the more saline water of the oases. The level in the main fresh water lobe is lower than the limit (around 1. 0 mg/1) above which sensitive crops may be affected. Irrigation use of this water would therefore be satisfactory in this respect so long as boron build up in the soil is controlled.

2. 4. 5. 5. Trace metals

Analysis of eight trace metals were carried out on all pumped exploration production wells. The results are tabulated in the well completion appendices. In addition a representative series of metal analyses were carried out on other wells in the area which are included in Appendix II.

Metal solubility is controlled by a number of factors most important being the solubility and abundance of parent minerals, the eH of the groundwater and the extent of complex formation.

The trace metal values, determined on filtered and acidified samples are all very low, in many cases below the limits of detection and generally less than 0. 01 mg/1. Iron, zinc and manganese are the only metals to exceed this level but the observed levels are not considered atypical for the type of formation and certainly do not approach recommended safety limits. The main control on metal levels in this case is considered to be the relatively high eH level of the groundwater. At lower eH levels (corresponding to absence of O_2 in the groundwater) there could be a strong possibility of higher metal levels being attained. It is recommended therefore that the eH be measured as a first indication of anaerobic groundwater which might control higher metal levels; care must also be taken to prevent reducing conditions occuring during transit or distribution of the groundwater when metal uptake could occur.

2. 4. 6. Field chemical and equilibrium studies

Table 19. Field chemical analyses and derived parameters of PMM and Deep Miocene/Oligocene wells of Phase 1 Area

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

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

Measurements were made throughout the field programme of various parameters necessary to define certain chemical equilibria and corrosion properties of the groundwater. Measurements of pH, eH temperature and HCO_3 were made in the field and used with chemical analyses to find calcite equilibria and iron stability relations. The results are given in Table 19 and these were discussed earlier in the Interim Report. The main conclusions on the Phase 1 groundwaters are:-

1) that the equilibrium free CO_2 is low (generally less than 15 mg/l) and is not likely to be a serious factor in corrosion consideration.

2) Groundwaters in the PMM aquifer are saturated or supersaturated with respect to calcite and although down-hole encrustation is not very likely unless pumping is turbulent, transit pipes could be affected.

3) With one exception (JCP) all groundwaters in the Phase 1 development area have moderately high eH values and are oxidising; thus iron solubility should remain low (<0.05 mg/l) and the formation of protective ferric hydroxide coatings on mild steel well installations should be assisted. From the eH-pH relationships (Figure 17) it is seen however that some of the Phase 1 groundwaters plot fairly close to the field of Fe^{2+}stability. If the eH-pH were only slightly changed therefore, conditions would favour solution of much larger amounts of ferrous iron.

It is important to note that the eH-pH of PMM groundwaters in 103-A and D well fields which have been pumping for several years are also oxidising (Figure 17) and this suggests that on sustained pumping the eH-pH conditions should not change significantly. In additon, well corrosion in the PMM wells in the 103 fields has not been found a serious problem.

2. 4. 7. Isotopic analyses, palaeoclimate and groundwater age

A series of related isotopic and palaeoclimatic investigations were carried out in the study area and at Kufra to complement the geochemical analysis. Measurements of radiocarbon (^{14}C) and tritium (^{3}H) isotopes plus ^{13}C were made principally to establish the relative and absolute ages of the groundwater and stratification; oxygen stable isotope ratios were determined to assess the uniformity of the groundwater and its possible origins in relation to palaeoclimate and evapotranspiration. At the same time radiocarbon analysis was carried out on a variety of surface carbonaceous samples to try and assess the palaeoclimatic history of the region relating to groundwater recharge. The results are discussed in turn and their implication discussed in relation to groundwater movement both in the Phase I area and elsewhere in Libya.

2. 4. 7. 1. Sampling and analytical methods

See Interim Report, section 2. 3. 4. 10.

2. 4. 7. 2. Theoretical considerations

Carbon from a variety of sources may be contributing to the total measured ^{14}C activity and the activity is not generally related directly to the age of the sample. In temperate climates the main source of radiocarbon is that derived from CO_2 in the atmosphere and soil zone of the recharge area and this reservoir will be in approximate equilibrium with the existing vegetation (Ingerson and Pearson 1963). As percolation and flow commence, the radiocarbon is cut off from its source and the ^{14}C will start to decay (the half life of ^{14}C being 5560 years).;

The CO_2 reacts with carbonate minerals according to the equation

$$CaCO_3 + CO_2 + H_2O = Ca^{2+} + 2HCO_3^- \quad (1)$$

and if the carbonate does not contain radiocarbon the ^{14}C will be diluted in the ratio 1:1.

This idealised model may not hold in certain environments, since dilution by decaying fossil plant debris, by CO_2 from natural gas deposits or magnetic sources may occur; isotopic exchange reactions or ultrafiltration may also serve to lower the radiocarbon level. In addition, reactions may occur near surface resulting in greater than 50% uptake of ^{14}C in the total carbon concentration. If the simple model can be applied a correction factor (P) can be applied to the measured activity values (Ingerson and Pearson 1963) based on knowledge of the $\delta^{13}C$ ratio of the sample ($\delta^{13}C_{sm}$), on the ratio in limestone ($\delta^{13}C_{ls}$) and in plant material of the recharge area ($\delta^{13}C_{pl}$).

$$P = \frac{\delta^{13}C_{sm} - \delta^{13}C_{ls}}{\delta^{13}C_{pl} - \delta^{13}C_{ls}}$$

Marine limestones are found to have relatively consistent $\delta^{13}C = 0 \pm 3$. However, plants are

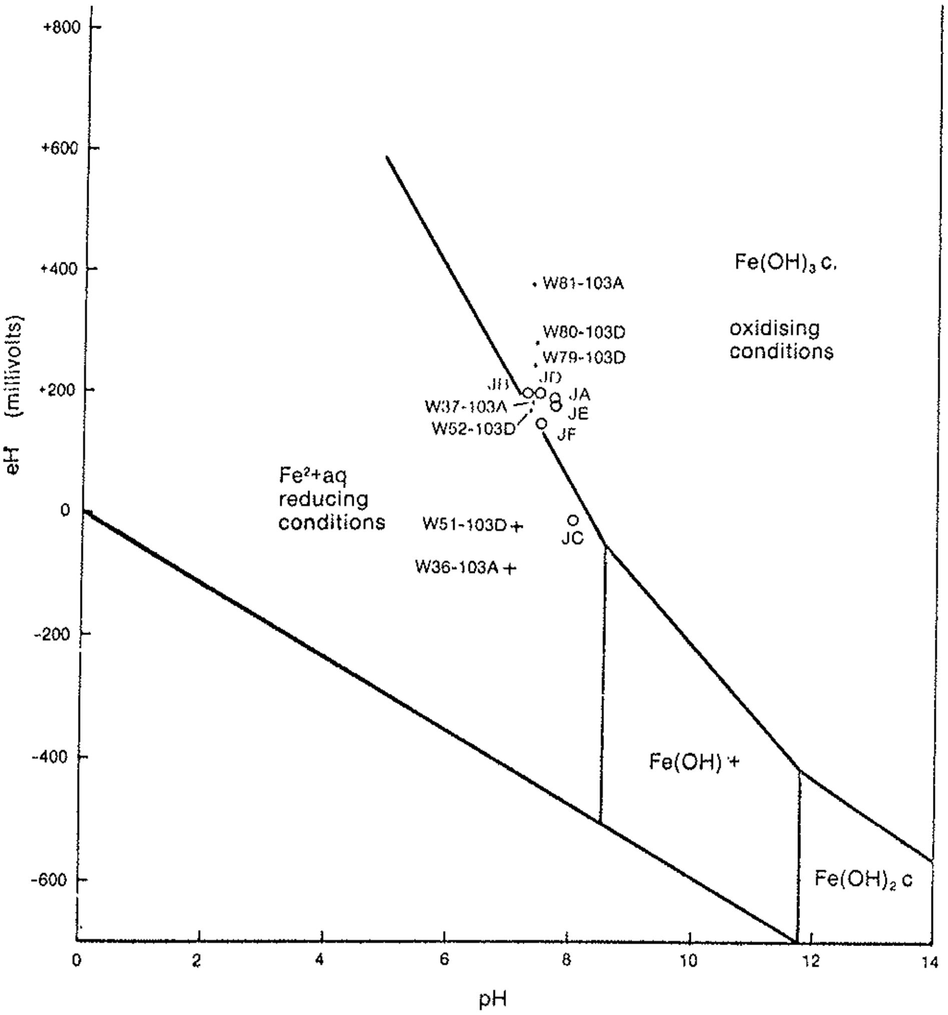

Figure 17. Stability field diagram (Eh-pH diagram) showing ferrous-ferric species and assuming 2 x 10^{-7} molar activity of iron

found to have widely varying $\delta^{13}C$ ratios (approximately -12 to -30) which makes the application of the formula correction and hence absolute radiocarbon dating rather difficult. In arid zones moreover recent studies have demonstrated that simple input models may also be invalid.

Because of the importance of the stable isotope correction in defining a model for ^{14}C transport to the reservoir, values for local carbonaceous material were ascertained during the investigation. Carbonised wood from soil pedestals; gave an average value of -21.5% whilst modern vegetation gave values ranging from -20.3 to -27.3% (see 2.4.7.4.1.). Calcrete samples gave $\delta^{13}C$ values of - 2.6 to -4.1% (Table 22); these latter values compare well with values for calcretes from N. America (Rightmire, personal communication).

The groundwater stable carbon isotope ratios from the PMM aquifer, however, (Table 20)show a range from -3.5% to -8.2% representing an enrichment in the heavier isotope over and above that which would be expected from the simple model of 50% uptake of soil CO_2 and 50% limestone CO_2; this value would be around $\delta^{13}C$ = -11%. The results suggest that the simple model cannot be valid in the present circumstances.

Carbon -13 enrichment could be due to carbon isotopic exchange, but although exchange reactions can be demonstrated in the laboratory (Thilo and Munnich 1970), most authors agree that such reactions are insignificant in the interpretation of groundwater ages in regional studies. Contribution of CO_2 from the underlying hydrocarbon reservoir can also be disregarded since this CO_2 would be very rich in ^{12}C.

Two models may be considered which could explain the observed data.

(1) Recent work by Lerman (1973) and Rightmire and Hanshaw (1973) has shown that plants which follow different photosynthetic cycles have different $\delta^{13}C/^{12}C$ ratios in their tissue and also in the equilibrium soil air. The lighter isotope enrichment ($\delta^{13}C$ = - 25) on which correction factors have traditionally been based is typical only of Calvin cycle vegetation. Hatch-Slack cycle plants however may produce values as low as - 10. Unfortunately desert vegetation usually has mixed vegetation types and it would be difficult to apply this information regionally without detailed knowledge of the ecosystems; in the present case it would be necessary to know the vegetation existing over a lengthy period of the Pleistocene, for example. Information on plant ^{13}C from the study area (see sections 2.4.7.4.1. and 2.4.7.4.2.) has so far shown that only plants with lighter isotope compositions occur.

(2) A second, more distinct possibility is that the heavier isotope enrichment is related to the aridity of the area of recharge. The bulk of radiocarbon interpretation has been carried out in samples from temperate zones. The present study however shows that most groundwaters are at or near saturation with respect to calcite and this implies that reaction (1) is at equilibrium and that CO_2 solution must have taken place at or near the surface.

Münnich and Vogel (1962) in a study of groundwaters from Egypt and coastal Libya also found ^{13}C enrichment in many waters. To explain these results (ranging from $\delta^{13}C$ = 3.4 to -11.7%). they discussed the possibility of CO2 uptake from a region devoid of vegetation. Experimental observations confirmed that the requisite CO_2 could be dissolved rapidly (1 - 5 days) in shallow pools of standing water. The equilibrium HCO_3^- in this environment was found to have a $\delta^{13}C$ value of -5%. In terms of the present study this would accord with the value of caliche of -4.1%.

Experience of storms during the present investigation shows that rain water is often held in shallow pools for several days due to air entrapment and to surface crusts. Against the second explanation however is the fact that plants do persist even in the aridity of the present day, and some soil activity must therefore occur.

It is considered likely that a combination of the latter two explanations is responsible for the enriched $\delta^{13}C$ ratios. Repeated evaporation of soil water in equilibrium with Hatch-Slack cycle plants could result in heavy isotope enrichment in groundwater recharge. It is therefore not considered practicable to find a reliable correction factor for the present study based on environmental knowledge of initial carbonate or CO_2 .

The initial ^{14}C therefore must be subject to some uncertainty. If CO_2 was derived in either of the ways described above and reaction was with dead carbonate in the aquifer, then a 50% figure for the initial ^{14}C activity would still be valid. However, it is a strong possibility that some of the carbonate carbon could be derived from caliche or near surface carbonate dust left by evaporation. This carbonate would contain radiocarbon so that the percentage of the total carbon in the groundwater could exceed 50% to give apparently younger ages. Radiocarbon results are quoted primarily as % modern carbon, although likely radiocarbon ages, have also been calculated from the expression:

$$\text{Age} = -8033 \ln \frac{A_m}{A_o} 0.75$$

where A_o = 85% of the standard count rate (Vogel 1970) and A_m is the measured activity. A value of 75% of the measured radiocarbon activity has been used to calculate age; this is intermediate between 50% recharge of 14C, which would correspond to thel:1 dilution equation, and 100% ^{14}C input. The errors are therefore $\pm \frac{3260}{2300}$ years. From the foregoing discussion the 75% value seems a reasonable estimate (c.f. Munnich and Vogel 1962). For the hydrogeological interpretation however, the relative age between groups of water, given by % modern carbon, are perfectly valid, and the ages are mainly quoted for a correlation with palaeoclimate.

2.4.7.3. Radiocarbon and ^{13}C results - ground waters.

2.4.7.3.1. Groundwater - Phase 1 Area

Radiocarbon results from 12 samples taken during the current investigation from the Phase 1 area are quoted as % modern carbon in Table 18. In addition, 7 results from Kufra water wells taken during the 1972-3 sampling period, are included.

The network of radiocarbon results was limited by the frequency of pumping water wells; air lifted samples which could have been contaminated by modern carbon were not considered, and all results are from localities where submersible pumps were in use. In the Phase 1 area 5 samples are from the exploration wells drilled during the present investigation and 7 are from pumping wells at oil camps. The approximate sample level is quoted in metres below the water table in Table 20.

Although results from the Phase 1 area show a wide scatter from 0 to 59.9% modern (6430 ± to >41270 B.P.) most of them are consistent with hydrogeological and palaeoclimatic knowledge of the area. There is a general relationship between 'age' and sample depth in the Phase 1 area. Thus, groundwater from JE-P and JD-P pumping from 44m below the water table have values of 5.4% (25770 ± B.P.) and 3.8 % (28580 ± B.P.) whilst two wells sampled in 103A and D Fields, pumped from 62-66m have values of 1.8% (34600± B.P.). Water from Augila 102-D Field pumping from only 19.0m has a value of 6.0% (24920 ± B.P.). An intermediate value of 3.1% (30210 ± B.P.) is also found at WW160-59E, pumping from a depth of 57m. Repeat samples were taken at different times from the same well at S1-103 but produced anomalous results. The value of 1.3% (37160 ± B.P.) is consistent with the depth sequence described above but a younger 'age' (17180 found from a sample taken one month later. It is unlikely that this represents a genuine heterogeneity in the aquifer but it is probable that the sample has been contaminated either by water leaking from a higher level in the aquifer or from air inflow from the sometimes defective pump. The result from B1-95 indicates groundwater older than the limit of detection (>41270). This sample, however, was derived from the Lower and Middle Miocene and the significantly greater age is consistent with this.

If anomalous results are rejected, the PMM group of results denotes a stratification in the aquifer such that between 44m and 76m below the water table an 'age' increase from 25770 to 37160 is found, representing, tentatively, an accumulation of groundwater during the main pluvial at an approximate rate of 1 m/350 years; this calculation is valid since the ages are here used in a relative sense. An anomalously young groundwater (9300± B.P) is found at E1-105, which is situated in the centre of the subsidiary zone of fresh water, considered to be associated with the line of a former wadi; the water is abstracted from a depth of approximately 76m below the water table. The chemical and radiocarbon results together confirm that this must be a late recharge event, superimposed on the regional pattern.

A model for the development of this freshwater body via wadi recharge and explaining also the localised low $\delta 13\ C$ ratios, is shown schematically in Figure 18; in this a climatic period characterised by relatively low rainfall (200mm/yr) concentrated in storms is assumed. Area recharge by direct infiltration is negligible and leads to the build up of soil carbonate and caliche deposits which, in turn, reduce the surface permeability. Storm run off is collected in the wadi system, simultaneously taking up dissolved CO_2 (low in ^{12}C) and attaining an equilibrium with calcium carbonate before infiltration via the wadi bed. The calcium carbonate source would be mainly caliche and surface dust containing a mixture of dead and radiocarbon rather than limestone carbonate. Recharge of $\delta^{13}C$ rich groundwater probably near carbonate saturation created a freshwater mound which had a thickness of at least 70m. According to the Ghyben-Herzberg relationship,

TABLE 20

Radiocarbon, stable carbon and oxygen isotope results on groundwaters Phase 1 area and KUFRA

SITE	SAMPLE DATE	SAMPLE METHOD (1)	APPROX SAMPLE DEPTH(2)	$^{13}C_{(3)}$ PDB	% MODERN CARBON(4)	CORRECTED CARBON 14 AGE (5)	$^{18}O_{(6)}$ SMOW	AQUIFER
PHASE 1								
JE-P	2/73	Na OH	44. 2	-5. 9	5. 4	25770±	-8. 9	PMM
Camp D-102	2/73	Na OH	19. 0	-6. 2	6. 0	24920±	-8. 5	PMM
JD-P	2/73	Na OH	44. 1	-6. 4	3. 8	28580±	-8. 7	PMM
$E1\text{-}105_1$	2/73	Na OH	73. 5	-3. 6	41. 9	9300±	-9. 0	PMM
$E1\text{-}105_2$	2/73	Na OH	73. 5	-3. 6	42. 2	9240±	-	
$SI\text{-}103_1$	1/73	Na OH	76. 0	-7. 2	1. 3	37160±	-9. 7	PMM
$SI\text{-}103_2$	2/73	Na OH	76. 0	-7. 2	15. 7	17180±	-	PMM
WW35 - 103A	2/73	Na OH	66. 3	-7. 1	1. 8	34600±	-9. 0	PMM
BI-95	2/73	Na OH	43. 4	-8. 2	0. 0	41270	-8. 9	MIOCENE
WW52 - 103D	2/73	Na OH	62. 0	-6. 0	1. 8	34600±	-	PMM
WW160 - 59E	2/73	Na OH	56. 9	-7. 0	3. 1	30210±	-9. 4	PMM
W 36 - 103A	2/72	IER	646	-11. 3	1. 3	37160±	-10. 2	OLIG
GATMIR	12/73	Na OH	8. 0	-4. 9	59. 9	6430±	n. d.	PMM
JALU (OMAR FADEL WELL)	12/73	Na OH	8. 0	-3. 2	57. 2	6800±	n. d.	PMM
JALU (ABDALLA REJAB WELL)	12/73	Na OH	8. 0	-5. 2	43. 7	8960±	n. d.	PMM
KUFRA								
KUFRA WW9	3/72	IER	112-310	-10. 1	5. 6	25470±	-11. 9	NUBIAN
KUFRA WW11	3/72	IER	112-222	-10. 7	0	44150	-11. 8	NUBIAN
KUFRA C 96	6/73	IER	240-340	-8. 1	0. 8	41100±	-12. 0	NUBIAN
KUFRA C 113	6/73	IER	142-264	-8. 5	0	42870	-12. 0	NUBIAN
	6/73	IER	100-322	-10. 5	2. 2	32980±	-11. 8	NUBIAN
KUFRA C 120	6/73	IER	104-246	-6. 7	0. 9	40100±	-10. 9	NUBIAN
KUFRA C 44	6/73	IER	100-230	-8. 6	6. 3	24510	-12. 0	NUBIAN

Notes :

(1) Na OH = Collection of CO_2 in Na OH trap
IER = Collection of CO_2 on strong acid anion exchange resin

(2) in metres below the water table

(3) $\delta^{13}C$ = for definition see text

(4) % modern carbon = measured ^{14}C activity/(reference activity x 0. 85) x 100

(5) Corrected carbon 14 age $\pm \frac{3240}{2300}$ years. For method of calculation see text.

(6) $$\delta^{18}O = \frac{R\,\text{sample} - R_{SMOW}}{R_{SMOW}} \times 1000$$

Where R is the ratio of $^{18}O/^{16}O$ and SMOW is Standard Mean Ocean Water.

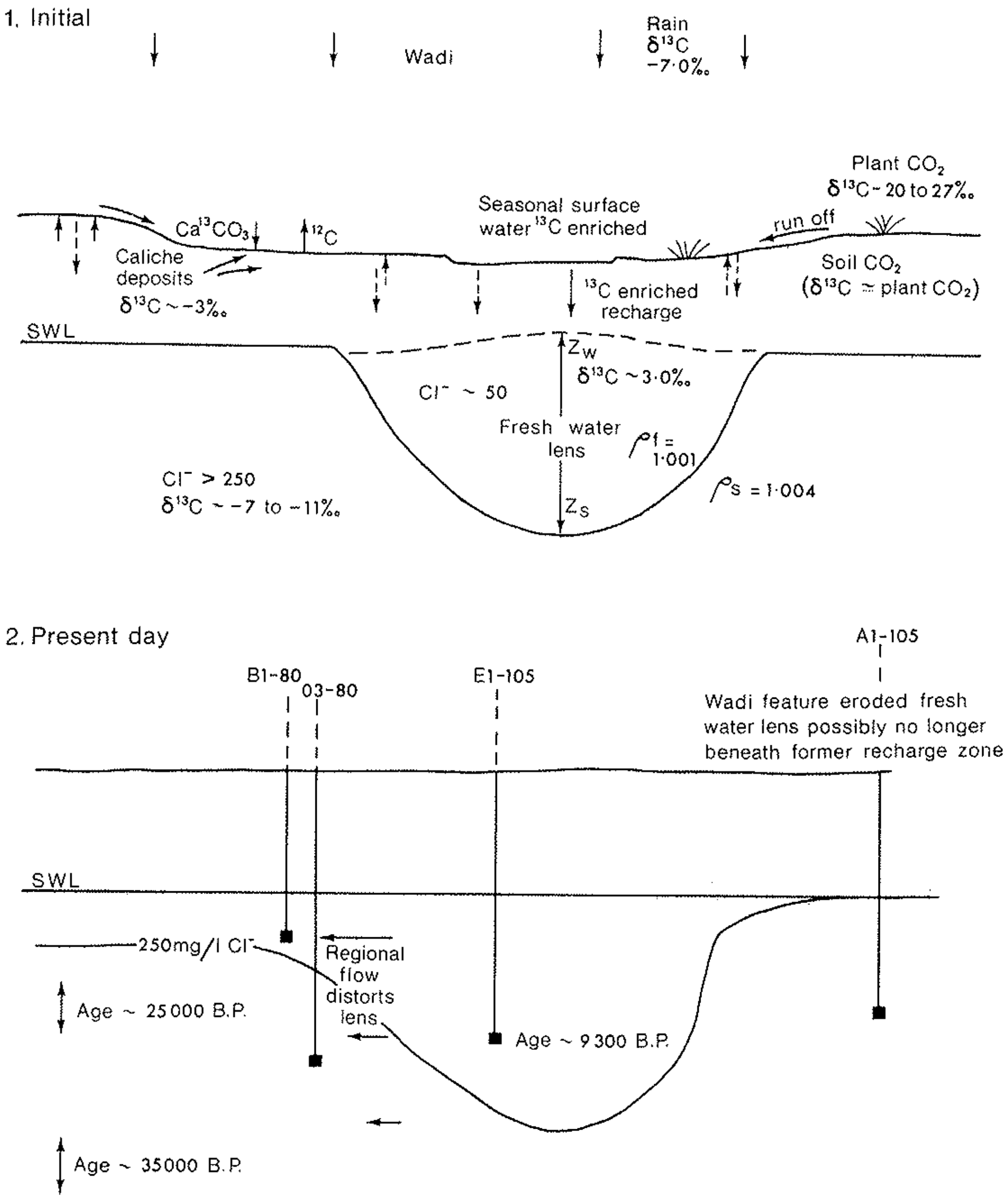

Figure 18. Schematic representation of the evolution of the fresh water lens and recharge of ^{13}C enriched groundwater.

$$Zs = \frac{\rho f}{\rho s - \rho f} Zw$$

this thickness of freshwater (Zs) could easily develop with local water table head differences of 0.5m and the observed salinity differences. It is noted that the water could have moved a considerable distance in the 9000 years since infiltration. On the basis of transmissivities, hydraulic gradients and time this distance is likely to be of the order of 50km and the area of recharge may be further to the south than the present position of the lens. Shallow groundwater from Gatmir oasis gives an age of 6430± B.P. (59.9% modern). This sample is from the well which is pumped frequently for Jalu water supply and although irrigation, recently commenced, is carried out nearby, significant contamination is discounted for this site. Gatmir provides further evidence therefore that groundwater, younger than the main pluvial phase exists in the desert, although at shallow depths, (unlike at El-105) and lends support to the idea that a thin layer of young fresher water may exist at near the top of the saturated part of the aquifer.

The wells at Jalu sampled for 14-C also give young ages, 43.7% modern (8960± B.P) and 57.2% modern (6800± B.P.). These two wells are situated on the eastern edge of the oasis (see Figure 10). Both wells are pumped for local irrigation use. Abdallah Rejab Well had been in use for at least 1 year prior to sampling and Omar Fadel Well had been in use for a few months. Recycling of water with risk of uptake of modern-carbon soil CO_2 is a possibility although the results are consistent with those from Gatmir. Stable carbon isotope ratios at Jalu and Gatmir are similar and correspond with the heavier ratios found at El-105, suggesting a common recharge history as discussed earlier for the younger water although a different recharge history to the deeper, older groundwater.

Deep groundwater from the Oligocene sampled in 103A wellfield gave a positive age 37160 ± B.P. (1.3% modern) and suggests a fairly rapid movement of groundwater in this confined aquifer.

2.4.7.3.2. Groundwater -Kufra

Samples of groundwater from Kufra were taken on two occasions, in 1972 and 1973 and are conveniently included in this report to clarify the regional relationship. In the initial sampling only two wells WW9 and WW11 on the first experimental farm were sampled and these gave widely differing results (Edmunds 1972). This was anomalous since the screened interval in the wells commenced at the same datum although WW9, which gave a higher value, (4.9% 20212 ± BP) had a greater drilled drilled depth than WW11 (0%). Assuming that no leakage through or down the casing had occurred, two explanations were considered:

(1) Stratification. It is known that two aquifers exist at Kufra, a water table aquifer and a semi-confined aquifer in which the well field has been developed. Natural age stratification would probably occur in the groundwater and it is possible that the younger age represented draw-down of younger water.

(2) Recycling of irrigation water. Both samples were from the oldest part of the experimental farm and it is possible that recycled water, which would pick up quite high $^{14}CO_2$ in the soil zone, had contaminated the sample. As little as 5% recycling could explain the observed contamination.

In an attempt to resolve the age discrepancy, the further series of samples was taken in 1973, and in addition, samples were taken for stable isotope analysis. All five wells sampled are from the deeper, semi-confined aquifer. A constraint was placed on the range of samples which could be taken by the rather consistent depth to which wells were drilled and screened - all samples were derived from depths in excess of 100m below the water table. No samples could be obtained from the shallow aquifer due to a lack of suitable wells, It is recommended that further sampling can be made of the shallow groundwater as boreholes are drilled.

It can be seen from the results in Table 20 that the most probable age of the main groundwater unit is around 40 000 years. However, the existence of ages both older and younger than this might reflect mixing with water of different ages from the top and bottom of the open well sections. Since the two younger waters (WW9 and C78) were found in two wells with the highest screen settings, it is most reasonable to suppose that younger water has been drawn down from higher levels. Contamination by recycling seems, therefore, a much less likely possibility than age stratification within the semi-confined aquifer.

2.4.7.4. Radiocarbon results - biological material and calcrete

A variety of biological samples were collected from the Phase 1 area and Kufra to provide confirmatory evidence for the radiocarbon investigations and to investigate the palaeoclimate. No specific sampling was carried out but suitable material encountered during field surveys was considered for analysis. The results quoted as B.P. are given in Table 22.

2.4.7.4.1. Modern vegetation

Three samples of modern vegetation were taken in order to check on $\delta^{13}C$ values in typical plants of the present-day environment as a clue to possible former species; the results are given in Table 21.

TABLE 21

Stable carbon isotope ratios of modern Libyan vegetation

Plant	Location	^{14}C (% modern)	$\delta^{13}C$ %
1. Palmetto	Gatmir	50.4 ± 0.6	-27.3
2. Small silver-leafed unidentified plant, flowering after heavy rain	Near S1-103	51.6 ± 1.3	-20.3
3. Alfalfa (N.B. not native to area)	Kufra	52.8 ± 0.8	-26.4

These results indicate that the plants are enriched in the lighter (^{12}C) isotope. From measurement of the stable ratios of both modern and fossil plant material no plants with -δheavy isotope (Hatch-Slack) enrichment have been detected, supporting the explanation of enrichment proposed in section 2.4.7.2.

2.4.7.4.2. Soil pedestals and wood

Soil pedestals are occasionally found in the Phase 1 area, notably within a 50 km radius of Jalu Oasis. Two of these pedestals, near D18-102 and D1-97, which were respectively 6m and 10m high were sampled for representative material. The former pedestal stood in an area of sparse existing vegetation where the water table was approximately 4m below surface level, but the latter, a huge isolated pedestal was in an area where the water table was at least 10m below surface level.

All samples of wood were found to be less than 1000 years old. This has important implications with regard to the erosional rates in the area, since the soil pedestals are clearly residual. It is considered probable that soil layers up to 10m thick were built up during previous wetter periods and have been eroded subsequently, but also that these parts of the soil cover were near enough to water table to be able to support vegetation in recent historic times. These pedestals were probably protected by small clumps of deep-rooted palms. As well as a rapid erosional rate resulting from a drier climate, possibly accelerated by grazing of animals, it is also evident that a regional decline in water level has occurred.

A series of wood samples from soil pedestals at Kufra was also analysed. Samples were taken from above and below a 0.5m thick horizon of rock salt. This horizon, from evidence elsewhere in the Oasis, would mark a former sebkha level, and was estimated to be at least 5m above the present water table at Kufra. Dating of material above and below this salt horizon should therefore fix the age of the former high water table.

Results indicate that the wood above the halite layer is slightly younger (2632 ± BP) than the wood beneath the salt (2996 ± BP) and that the water level must have naturally declined at least 5m to its present level in around 3000 years.

2.4.7.4.3. Ostrich eggs

Fragments of ostrich shell were found on the surface in two separate localities of the Phase 1 area. Isolated fragments, partly wind eroded were found immediately south west of S1-103 whilst slightly charred shell fragments were found at the site of a neolithic encampment several kilometers north-east of A1-105. Associated with this site were various implements including scrapers and bolas stones. From geochemical considerations it is unlikely that exchange of ^{14}C with the shell debris would have occurred and the fragments are considered suitable for dating pur-

TABLE 22

Stable carbon isotope and radiocarbon analyses of fossil biological samples and calcretes

SAMPLE DESCRIPTION	LOCATION	RADIOCARBON LABORATORY NO,	$\delta^{13}C$ (% PDB)	RADIOCARBON AGE
PHASE 1 AREA				
Plant debris from isolated soil pedestal N. E. of D18-102	29° 10' N 21° 32' E	SRR-81	-16. 7	788 ± 50 BP
Ostrich egg shells-fragments within neolithic camp.	28° 27' N 22° 03' E	SRR-201	-6. 9	8465 ± 56 BP
Ostrich egg shell fragments, isolated, lying on desert surface	28° 43' N 21° 00' E	SRR-202	-7. 0	4169 ± 45 BP
Wood fragments (tamarisk) from large soil pedestal 6m high, 30km SE Jalu.	28° 22' N 21° 51' E	SRR-207	-22. 0	1005 ± 50 BP
Alkali-soluble carbon recovered from SRR-207	- do -	SRR-208	-21. 5	815 ± 75 BP
Carbonised wood fragments from same site as SRR-207	- do -	SRR-209	-24. 2	621 ± 50 BP
Conglomerate of wood fragments and tamarisk needles (treated to remove humics and carbonate)	- do -	SRR-210	-23. 4	425 ± 60
Calcrete 30 cm below surface	28° 42' N 21° 11' E	SRR-332	-4. 1	25560 ± 180 BP
Calcrete (Phase 2 area) surface sample	27° 41' N 22° 07' E	SRR-333	-2. 6	31800 ± 370
Calcrete (Phase 2 area)	27° 41' N 22° 07' E	SRR-334	-2. 6	>46500
KUFRA				
Wood from soil pedestal or edge of oasis, 1m above halite horizon	24° 13' N 23° 17' E	SRR-217	-21. 0	2632 ± 50 BP
Wood from base of soil pedestal		SRR-218	-22. 1	2996 ± 50 BP

poses.

The ages of the two samples, 4169 ± BP indicate that vegetation cover probably existed over this area in the post-pluvial period and the existence of a camp at this site indicates that surface water was probably also available at least seasonally. The importance of the latter egg shell date lies in the coincidence of the site with the fresh water lens referred to above (section 2.4.7.3.1.) and the similarity of the ages of the shell with the groundwater lens. This is further evidence of the existence at that locality of a recently active wadi system.

TABLE 23

Tritium analyses on samples from Phase 1 area and Kufra; results are ± 2.0.T.U.

SITE	SAMPLE DATE	SAMPLE DEPTH	TRITIUM (T.U.)*
AUGILA OASIS	2/72	4 m	-0.7
AUGILA OASIS	2/72	4 m	0.2
AUGILA OASIS	2/72	4 m	-2.7
F2-102	2/72	50 m	-2.0
D28-102	2/72	25 m	-0.3
JALU	2/72	5 m	-0.5
JALU	2/72	4 m	-0.6
D17-102	2/72	25 m	3.2
KUFRA WW 9	3/72	112 m	-0.5
KUFRA WW 11	3/72	112 m	0.7
KUFRA (EAST)	3/72	4 m	0.5
KUFRA WW 4	3/72	50 m	1.6
KUFRA (ALMANI)	3/72	3 m	4.0
RAIN (S1-103) (08.00)	6.4.72	-	97.0
RAIN (S1-103) (08.30)	6.4.72	-	97.3
RAIN (S1-103) (14.25)	6.4.73	-	122.2
* 1 TU = 1 tritium atom per 10^{18} hydrogen atoms.			

2.4.7.5. Tritium results

The possibility of recent recharge, although remote, was checked using natural tritium, which occurs in the atmosphere and in rain as a result of thermonuclear testing. Its presence in groundwater therefore indicates a component of post-1953 water. Sampling was also carried out to check on results quoted by Eskangi (1968) from Kufra and elsewhere which were strongly positive. The sample localities and results are given in Table 23, groundwaters analysed were derived from both shallow wells and a few control samples from deep wells. Analyses were made by the Atomic Energy Research Establishment, Harwell, U.K.

Shallow groundwaters from dug wells in the Augila and Jalu area all indicate no recent recharge and this is also true for shallow wells in the area.

Deep wells at Kufra are free of tritium but there is a trace of tritium in one shallow well within the Oasis (Almani). This does not necessarily indicate slight recharge but rather a degree of contamination. It was possible to check the level of tritium in rainfall during a storm near S1-103 in April 1973 during which one inch of rain fell over a period of 12 hours. Tritium levels at that time ranged from 97 T.U. at the beginning to 122.2 TU at the end of the storm.

2.4.7.6. Stable isotope Results (oxygen and hydrogen)

Representative samples were collected for oxygen and hydrogen stable isotope analysis

TABLE 24

Oxygen isotope results

SITE	SAMPLING DATE	SAMPLE DEPTH	^{18}O (SMOW)	PUMPED OR DEPTH SAMPLE
JC-P	13.10.72	107	-9.0	P
J(KK1-12)	6.8.72	107	-9.4	P
JB-01	19.1.73	(PUMPED)	-8.9	P
JB-01	19.1.73.	90	-9.3	D
JB-01	19.1.73	110	-8.7	D
JB-01	19.1.73	130	-8.9	D
JD-01	19.1.73	130	-8.9	D
A1-LP5C (WW South)		90	-9.2	P
WW81-103A	19.1.73	138	-8.9	P
A1-102	20.1.73	44	-7.6	D
G1-6	30.1.73	139	-7.9	D
H3-6	3.2.73	181	-7.1	D
RRR1-59	29.1.73	216	-8.9	D
AAAA1-59	29.1.73	?	-9.3	D
DDDD1-59	28.1.73	112	-9.6	P
P5-59	23.1.73	80	-8.1	D
P10-59	23.1.73	?	-8.7	D
GATMIR	21.1.73	4	-0.5	P
JALU (8km NW)	21.1.73	8	-7.1	P
JALU (1km NE)	21.1.73	3	-5.4	D
JALU (2km W)	21.1.73	8	-7.8	P
AIN ARBIYAT	2.2.73	1	-7.1	D
AIN ZUBAIRI	4.2.73	1	-6.9	D

from Phase 1 area wells. At the time of writing, results for oxygen only are available, and these are presented in Tables 20 and 24; preliminary conclusions can be drawn from the oxygen results alone.

It is clear that the groundwater from the PMM in the Phase 1 area is of uniform $\delta^{18}O$ composition with a mean value of 8.9 ± 1.0‰. In contrast, the Kufra groundwaters have $\delta^{18}O$ values of 11.9. ± 0.1‰ with one exception and this indicates a separate source for the groundwaters in the Kufra and Sirte Basins. The uniformity of oxygen isotope results in the Phase 1 groundwater is consistent with the geochemical evidence but contrast with the age layering as shown by the carbon 14 results; it is clear that there must have been no significant palaeotemperature fluctuations during the period of main recharge (i.e. 25000 - 35000 years B.P.)

In contrast with the main groundwater body, the results from the oasis areas show that slight enrichment in the heavier (^{18}O) isotope has generally occurred. This enrichment (e.g. around 2.0‰) however is probably not sufficient to indicate that the salinity increase observed around the oasis is entirely due to contemporary evapotranspiration; it is more likely to support the theory that the main body of groundwater has entered the oasis without appreciable loss of the lighter isotope and has dissolved salts concentrated in the formation by previous evaporative cycles (see section 2.4.3.6.). A further discussion of the results is deferred until the deuterium analyses can be considered.

2.4.7.7. Palaeoclimate

The radiocarbon results, stable isotope results and geomorphological evidence from the present study can be used in conjunction with available published data from Libya to reconstruct the palaeoclimate and assess the conditions of recharge; correlation with results from elsewhere in North Africa has not been attempted in this report.

A detailed chronology and palaeoclimate for Northern Cyrenaica has been established by McBurney (1968) in his recent classic study of the Haua Fteah cave deposits. The palaeoclimate was established on the basis of Carbon 14, stable isotope studies and investigations of mammallian remains and is one of the most detailed for any area in the Middle East. The main results from the study are used as a basis for the present discussion; even though they have to be extrapolated from a coastal to an inland environment the relative differences are probably similar to those of the present day. The main events are shown in Figure 19 and it is seen that a main uninterrupted cold, wet period (Wurm Glaciation) occurred from about 35000 - 11000 years B.P. followed by a rapid change of climate towards the present day. Palaeotemperatures measured on shell debris from the cave (Emiliani et al. 1963) showed an average annual value of 16° C during the cold period but an increase of at least 5° C in the Post-Glacial period.

Little chronological evidence is available for the inland areas, but Ziegert (1966) suggests that sediments in the Fezzan can be correlated with pluvial periods and by dating these with archaeological finds, considers that a wet subphase occurred at around 6000 years BP. Corroboration of a later humid phase in southern Libya (Ubari and Tejerhi areas) is provided also by Bellair (1953) who finds evidence of a neolithic humid phase.

The groundwater radiocarbon chronology for the Phase 1 area is shown diagramatically in Figure 16 where the relations between age, depth and palaeoclimate are shown. The bulk of the groundwater in the PMM aquifer in the Phase 1 area, at least to a depth of 80m therefore fell as rain during the main Wurm climatic period; in the LMM the water was recharged before this main cooler period. At Kufra it is likely that water presently beneath the Oasis, at depths of 120m or more was recharged near the beginning of this cold, humid period.

Evidence of this former humid phase is sparse over the region studied. Dissected Miocene limestone surfaces occur in the west of the Phase 1 area and broad wadis make gentle surface relief west and south west of Augila for example, but elsewhere the serir is almost without relief. Wadis that are found show evidence both of infilling and erosion, but these erosional processes must have been effective for only a few thousand years. Wadi lines have been defined quite extensively to the east of the area (di Cesare et al 1963) from aerial reconnaissance and physiographic survey, and it is likely that these features extend westwards into the Phase 1 area.

Confirmation of wadi development by detailed mapping could not be undertaken in the study, but the geochemical and age studies described above provide strong evidence that an important wadi existed in the south east which must have been active considerably after the end of the Wurm glaciation. Although no evidence for general recharge after the main pluvial Phase is found, this local evidence suggests that recharge by surface runoff to wadis occurred during a later

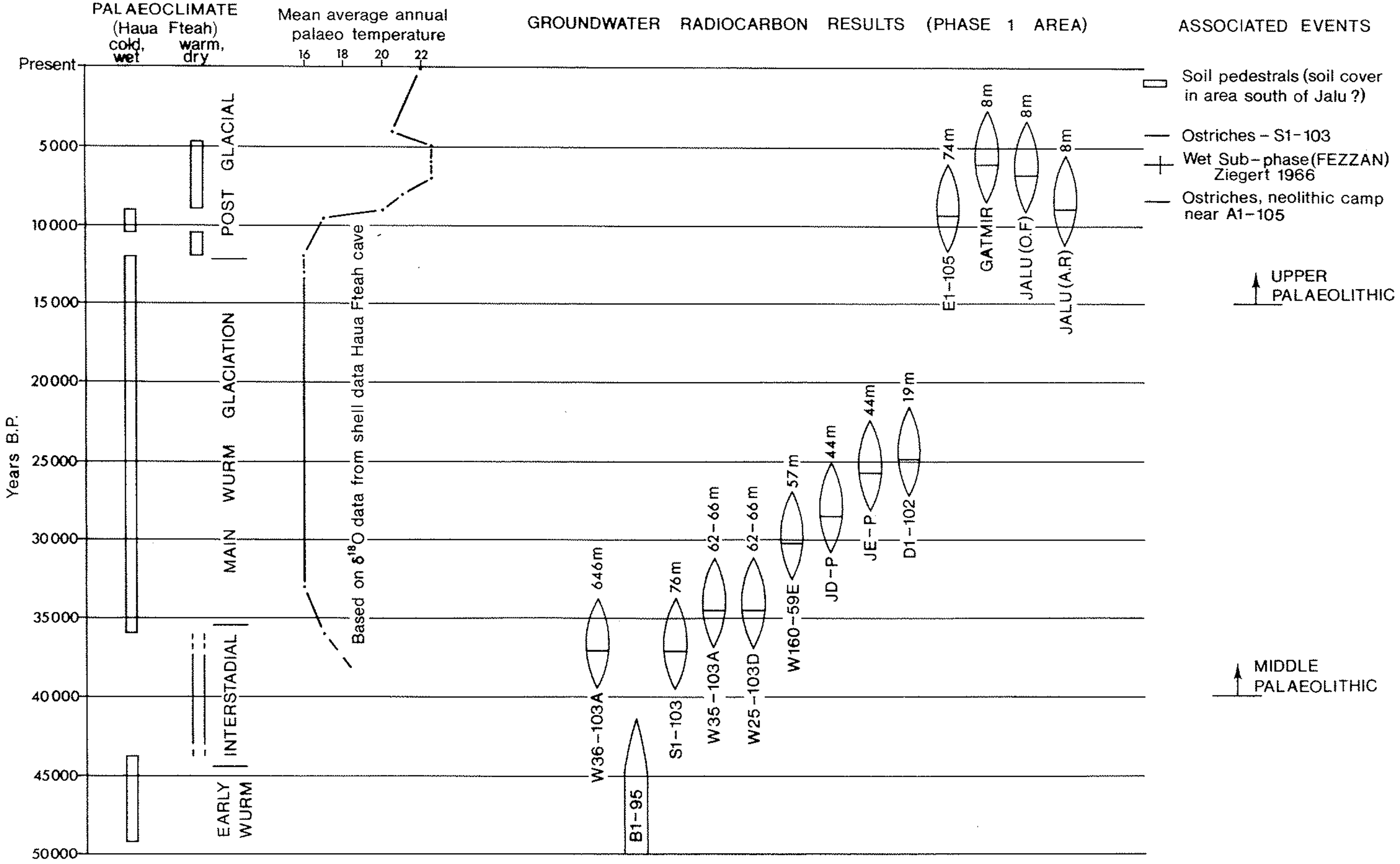

Figure 19. Groundwater ages in relation to the palaeoclimate of Libya during the past 50 000 years

stage. This wadi, for which no surface features could be found, could, however, coincide with an extension from one to the east (di Cesare et al 1963). Assuming a rainfall of 300mm per year and, say, recharge of 30% of this water via a wadi system with a catchment 10 times the surface area of the freshwater lobe, a freshwater lens 80m thick could be built up over a period as short as 800 years. The existence also of soil pedestals less than 2000 years old, probably remnants of a general extensive soil cover, testifies to the rapidity of erosion in the region. It is considered probable that similar freshwater bodies may exist elsewhere in the Phase 1 area and this fact should be borne in mind during development; a thin layer or lens of fresh groundwater may be superimposed on the main groundwater body undetected by developing the total saturated thickness of the aquifer.

Note added in proof:

A study of Saharan palaeoclimate was published as this report was being finalised (Geyh and Jäkel, 1974). These authors conclude that since the end of the Pleistocene humid period (around 11 700 B.P.) several humid episodes have followed, separated by more arid climate. Humid periods are postulated from 10 500 - 8700 BP, 6000 - 4700 BP and from 3700 BP to the present there have also been humid periods. This evidence would support the view proposed above, that groundwater recharge has occurred during one or more periods since the end of the pleistocene.

2.4.8. Water quality and groundwater use

2.4.8.1. Domestic use

The maximum permissable limit for total mineralization in drinking water according to the World Health Organisation (Anon 1971) is 1500 mg/1. This level is reached or exceeded in the fresh water lobe of the Phase 1 area which is defined by the 2000 mg/l contour. In parts of Libya however public supply water of concentration higher than 1500 mg/1, is used and locally much higher levels have been tolerated by adaptation; at Augila and Jalu oases for example water from local wells, used until recently, has a total mineralization of up to 6000 mg/1. The present water supply for Jalu, obtained by tanker from Getmir, has total dissolved solids of 1953 mg/1. Therefore it is desirable that the least mineralized water in the Phase 1 area occurring in the southern half of the fresh water lobe, to be considered first for public supply use, but the potential reserves should include all groundwater below 2000 mg/1 in total dissolved solids. The best quality water in the area is undoubtedly the fresh water lens to the immediate west of A1-105, which has total dissolved solids of just over 500 mg/1.

Most water in the main fresh water lobe, from pumped samples during the current development programme (Interim Report, Appendix 12) contains sulphate in the range 300 to 600 mg/1 SO_4 and this crosses the World Health Organisation maximum permissable limit of 400 mg/1. It is important therefore that the sulphate level be taken into consideration for any water proposed for domestic use.

Minor and trace elements present in the groundwater must also be considered in relation to possible toxic effects. Details of trace element analyses made during this study are included in Appendix 12 (Interim Report) and their geochemical significance is discussed in an earlier section of this report (2.4.5.).

It has been mentioned that fluoride is present quite widely in the main area of fresh groundwater at levels at or above optimum levels for dental health (0.7-1.2 mg/1). The values found during the pumping test at JA remained constant at 3.6 mg/1 and this level of fluoride in a groundwater which is otherwise of acceptable quality could cause dental fluorosis. Further monitoring of fluoride is therefore recommended for all the fresh groundwater in the Phase 1 area.

Groundwater nitrate levels are generally below the WHO maximum of 50 mg/1 although JE-P, J(A1-LP3C) and J(F1-97) are slightly above this concentration. It is again recommended that nitrate contents are monitored further since sustained values higher than 45 mg/1 in public supply could give rise to toxic effects particularly methaemoglobaemia in infants. Nitrate levels elsewhere in eastern Libya are high and this problem was discussed in a region al context in a supplement to the earlier report (Wright and Edmunds 1969).

Eight trace metals determined on selected waters during the investigation are all at levels

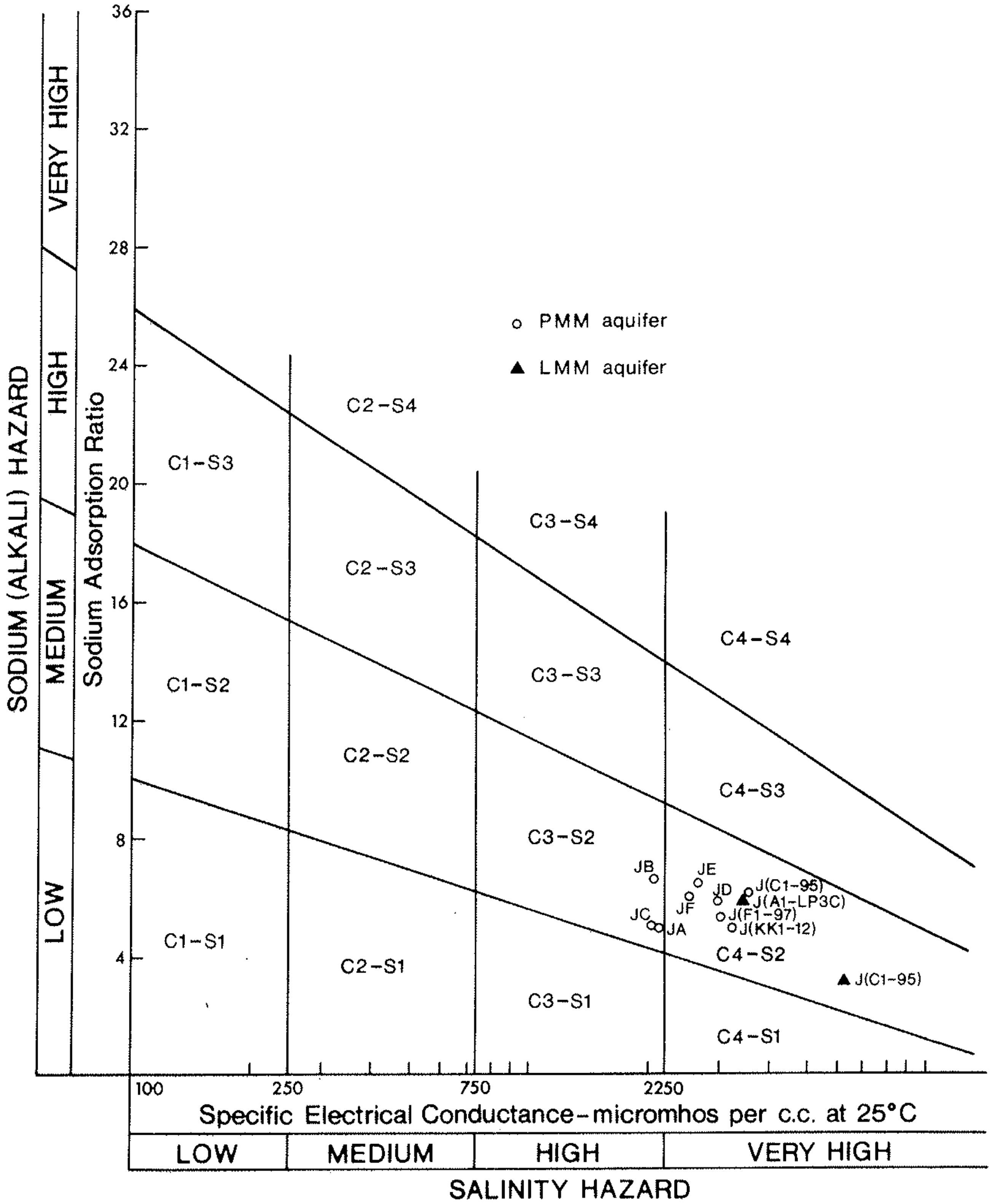

Figure 20. Classification of groundwaters from exploration/production wells for irrigation purposes

well below those considered dangerous for public supply. No determinations for chromium, arsenic or selenium were carried out but on the evidence of chemically similar elements it is unlikely that these would be present naturally at high levels in the groundwater. It is stressed that the results of this study refer only to the natural groundwater, and this may not relate to the finished supply particularly with respect to trace metals (cf. section 2. 4. 5. 5.)

No assessment of the water resources for bacterial purity has been carried out in this survey, but it is probable that in the natural state the groundwater would be sterile.

2. 4. 8. 2. Agricultural use

There is no single upper limit of total mineralisation for water for irrigation use, but the maximum practicable limit will depend on various factors including soil type, soil and bedrock permeability, crop type and ratio of ionic constituents as well as on total salinity.; Sodium absorption ratios (SAR) have been computed for all groundwaters where mineral analyses were made and the results are given in the Interim Report (Table 7 of Appendix 12). The SAR is a measure of the exchangeable sodium in the groundwater and values for most groundwater in the Phase 1 area lie between 4 and 6. 5. A high sulphate to chloride ratio in the water is an advantage and may have the effect of lowering the SAR.

Selected groundwaters in the Phase 1 have been clarified using the method adopted by the US Department of Agriculture to indicate their suitability for irrigation use; the results are shown in Figure 20. This plot is valid for 'average' soil conditions and it is probable that over much of the Phase 1 area the soil conditions are rather better than average and the diagram therefore expresses a pessimistic condition.

It is found that the waters plot in the C3-S2 and C4-S2 fields on this classification. The comments of the US. Dept of Agriculture circular are reproduced below.

'High salinity water (C3) cannot be used on soils with restricted drainage. Even with adequate drainage special management for salinity control may be required and plants with good salt tolerance should be selected.

Very high salinity water (C4) is not suitable for irrigation under ordinary conditions but may be used occasionally under very special circumstances. The soils must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching.

Medium sodium water (S2) will present an appreciable sodium hazard in fine textured soils of high cation-exchange capacity, especially under low leaching conditions, when gypsum is present in the soil. This water may be used on coarse textured or organic soils that have good permeability.'

Boron present in groundwater above certain limits may affect the health of certain boron-sensitive crops, notably citrus fruit. Concentrations in groundwater of 0. 5 mg/1 B or above may under various soil conditions, give rise to plant toxicity. Most waters in the central fresh water lobe contain about 0. 5 mg/1 B although higher values are found in the more saline waters. The boron levels are probably acceptable for all but sensitive crops, but it is advisable to consider the groundwater boron levels further in relation to intended irrigation and agricultural proposals.

2. 4. 8. 3. Quality in relation to well-field development

The field analytical programme, the results of which were discussed in section 6, was designed to provide basic data on the groundwater in its natural state which would be relevant to its development and distribution.

Corrosion is usually caused by the interaction of a number of factors and for a discussion of these the reader is referred to Barnes and Clarke (1969) or Clarke and Barnes (1969). In this report, a geochemical approach, similar to that of these authors has been adopted. Thus, the accurate measurement of field physico-chemical conditions provides information useful to assessment of corrosion problem. These results have been discussed above (Section 2. 4. 6.)

In general the field measurements indicate mildly oxidising conditions with calcium carbonate saturation or supersaturation and free CO_2 around 15 mg/1, for the PMM Phase 1 development area. These conditions are indicative of only mild corrosion. Evidence from 103-D well fields where wells in the PMM have been pumped for several years indicates from practical experience that corrosion is not a serious problem.

In comparison with Kufra for example where high free CO_2, low salinity contribute to corrosion problems, the PMM groundwater in the main development area should present no serious problems.

Corrosion rates were measured using a corrator on certain wells and results for a variety of metal probes are quoted in inches/yr in the various Appendices of the Interim Report. A consistent picture does not emerge however from these results, partly due to measurement difficulties, and it is recommended that further measurements be made if detailed behaviour of individual metals is required.

2. 4. 9. Principal hydrogeochemical conclusions

1. The extent of potable groundwater resources is based in this report on the 2000 mg/l total mineralization contour.

2. The main, fresh groundwater lobe in the PMM is a geochemically homogeneous body of water, the principal feature being that the total mineralization increases from 1000 to 2000 mg/l over a distance of 130 km along the flow path, this increase being virtually isochemical; quality stratification is rare. The groundwater is of mixed ionic composition with SO_4/Cl ratio generally just less than 1; the chemistry is controlled by groundwater movement through a geochemically homogeneous fluviatile sequence.

3. The boundaries to the fresh water lobe to the north and to the west are related principally to the lithochemical control of the Miocene (LMM).

4. The deterioration of water quality south east of Jalu is probably related to the presence of local alluvial deposits and thin associated evaporites within the PMM aquifer. The geochemistry of these waters can be distinquished from those in the fresh water lobe to the west by their lower SO_4/Cl ratios.

5. The distinct zone of good quality water west of A1-105 is a freshwater body at least 70 m thick and 5km wide superimposed on the regional groundwater body.

6. Saline water around Jalu and Augila is related geochemically to the less saline water immediately to the south. The deterioration is considered to be caused by <u>in situ</u> concentration by evapotranspiration and dissolution of residual salts, during water table fluctuations. This water may overlie less saline water.

7. Poor quality water north of Augila oasis is related to evaporites in the LMM aquifer.

8. Geochemical evidence is inconclusive in relation to possible upward or lateral leakage from the LMM to the PMM, particularly in the south of the area. Several lines of evidence however, including the overall homogeneous composition of the aquifer chemistry, the Mg/Ca ratios and Sr^{2+} concentrations seem to rule out significant (say $<10\%$) leakage from the LMM in the central and northern areas. Geochemical evidence however is consistent with flow from the PMM to the LMM in the north.

9. The groundwaters in the main freshwater lobe are generally saturated with calcite and are oxidising.

10. Radiocarbon analyses demonstrate that although geochemically homogeneous, age stratification occurs in the PMM aquifer. Ages measured in the main body of groundwater range from 37000 years B. P. at 75m to 25000 years at around 20m depth.

    The subsidiary lens of good quality water in Concession 105 has an age of 9300 years B. P. and this is clearly superimposed on the main aquifer and results from a later period of recharge.

11. Levels of nitrate and fluoride present in the groundwater give some cause for concern should the water be developed for extensive domestic supply. Other constituents investigated are below internationally accepted threshold limits.

2. 5. Water Resources of the Phase 1 Area

A basic survey of the water resources of the Phase 1 Area was presented in the Interim Report. The survey included a qualitative discussion of the potential of the LMM and Oligocene aquifers and a more detailed study of the more accessible PMM aquifer for which ground water models were prepared and to which two development schemes (A and B) were applied.

Modifications and additions to the data presented in the Interim Report are given here following further stratigraphic and analytical studies. These are concerned with:-

(a) An improved knowledge of the Miocene/Oligocene aquifers expressed mainly in the preparation of several detailed geological cross-sections, Map Figures 1-4. The discussion is still essentially qualitative.

(b) Implied changes in the boundary conditions of the PMM aquifer in relation to both the steady-state model and unsteady-state development schemes.

(c) Preparation of a modified mathematical model of the PMM aquifer incorporating an extensive clay layer. Development scheme B is applied.

(d) A development scheme (C) applied to the basic IGS model employing a well field designed by Tipton and Kalmbach and located in the central Phase 1 Area.

2. 5. 1. Miocene/Oligocene aquifers

The general discussion in the Interim Report covers the most significant aspects. As noted, water quality is likely to be a restrictive factor in any development of these aquifers to the north of 28° 40' latitude except in the upper levels of the LMM. The recognition that most of the wells to the north of 29° 00' latitude are within the Miocene does indicate that water quality in the shallow, confined Miocene below the PMM in the central Phase 1 Area is likely to be moderate to good. Upward leakage from the LMM to the PMM in this area would therefore not be a matter for concern.

Water quality in the deeper Miocene and in the Oligocene is generally poor in the central Phase 1 Area and presumably persists to the north down the hydraulic gradient. Quality probably improves to the south consonant with lithological changes. Confirmation is provided by data from the deep borehole to 2800' at Q1-65 immediately beyond the southern boundary limit. Discussion of these results will be deferred and included in the Phase 2 Report.

Although no quantitative data on the physical characteristics of the Miocene/Oligocene aquifers are available other than the localised results from the production wells at Occidental A and D Fields, Oasis Gialo and Amoseas Nafoora fields, general indications can be obtained from the geological cross-sections referred to above. Productivity is likely to be greater in sections with significant sand percentage. It should be recognised however that direct comparison cannot be made with the unconsolidated PMM sands. Factors such as cementation or clay content could have important consequences. With this proviso, the most favourable locations appear to be in the south and south-east of the Phase 1 Area and also within shallow Miocene deposits in the west and north. The thickness of the shallow Miocene sands in the latter areas is not very considerable but their location in relation to possible coastal supplies increases their importance.

2. 5. 2. The PMM aquifer

Consideration of the groundwater of the PMM aquifer has involved the construction of steady-state and transient ground water flow models. Two development schemes were investigated with the basic transient flow model and discussed in the Interim Report. The model assumed unconfined aquifer response and a specific yield of 0. 1 (10%). The schemes were as follows:-

(1) Development scheme A has a discharge of 41 000 m^3/day from each of eight centrally located well fields for periods of up to 25 years. Total discharge is 328 000 m^3/day.

(2) Development Scheme B has a discharge of 4636 m3/day from each of 33 individual wells spaced over the main central (1200 sq. km) area underlain by good quality water. Total discharge is 153 000 m^3/day. All pumping tests carried out to date in the PMM aquifer have been for short periods only during which the aquifer responded in either artesian or leaky artesian fashion. The effect was attributed to clay layers occurring above the screened production interval and confirmation has been provided by the detailed aquifer analysis (section 2. 2). Either condition will result in increased drawdowns in comparison with unconfined aquifer response and the significance of this effect in the long term behaviour will have to be established. In section 2. 5. 2. 3. a modification of the basic IGS model is discussed which incorporates a thin (3m) clay layer of low vertical

permeability (0. 007/0. 001 m/day) occurring above the general production well screen level and extending over the main well field area as used in Scheme B. Although geological evidence does not indicate the existence of such an extensive single layer, the concept is admissable as being equivalent to a series of over-lapping layers.

The three designed groundwater abstraction well fields tested to date on the models are all located in the central Phase 1 area where saturated aquifer thickness is in the range 80-100m and the dissolved solids content is less than 2000 mg/l. In assessing the practical significance of predicted drawdowns, appropriate pumping levels must be evaluated. Specific capacity will depend, among other factors, on screen length and a compromise must be made in screen and casing length, the latter being related in this instance to available drawdown. The relation assumes that the pump will not be set within the screened section. Details of specific capacity results in the test production wells are given in Table 25.

may well prove to be relatively stable.

The tested well fields were located in the central fresh water lobe with dissolved solids content less than 2000 mg/l. An increase in dissolved solids content occurs in the eastern Phase 1 Area. General values are in the range 2000/4000 mg/l with a further increase to above 6000 mg/l in a localised area to the north of Jalu Oasis. In the schemes modelled, predicted cones of depression do not attain the 4000 mg/l contour within 50 years, and on this basis significant deterioration in quality is not to be expected in this period. Regular monitoring of water quality is of course essential, particularly in the more easterly wells.

For considerations of soil characteristics and social/economic factors, agricultural schemes in the general vicinity of Augila-Jalu have been proposed, with the necessary water being brought from the central Phase 1 Area. If water of increased dissolved solids content in the range 2000/4000 mg/l could be used, then in-situ abstraction at the proposed locations may be possible . Favourable features include the increase in saturated thickness and estimated transmissibility in the eastern Phase 1. The main unfavourable feature is the presence of the zone of more highly saline water to the north of Jalu Oasis. An increase in dissolved solids beyond 4000 mg/l is probably undesirable for even salt tolerant crops and hence abstraction from the high salinity zone referred to would need to be avoided. There is some evidence however indicating that dissolved solids content may decrease with depth, although the decrease is unlikely to extend below the general range 2000-4000

TABLE 25

Phase 1 production wells specific capacity results.

Well	Saturated aquifer thickness (m)	Screen length (m)	Specific capacity (litres/sec/metre)
JB-P	92	60	3. 7
JC-P	80	46	5. 1
JD-P	88	52	4. 1
JF-P	75	49	2. 5
JE-P	74	49	2. 9

For a specific capacity of approximately 3 litres/sec/metre, a screen length of some 50m will be necessary with a consequent available drawdown in the range 30-50m. Since wells pumping at 60 litres/sec are required, a pumping drawdown of 20m will be superimposed on regional interference drawdowns. Specific capacity will decrease with time but in the circumstances of the proposed development, it will probably correlate fairly closely with the transmissibility of the main responding interval opposite the screened section. Until regional drawdowns attain the upper level of this interval, specific capacity mg/1. Further drilling and testing would be necessary to prove these indications, but in the circumstances the costs would seem to be well justified.

Recent results which have become available during the final stages of the present investigation have added to or modified the concepts upon which the modelling studies detailed in the Interim Report were based. The significance of the changes and additions must be considered in relation to the schemes already modelled. These changes include:-

1. The recognition of the so-called Aklash Formation as being of Middle Miocene age.

2. Evidence of leakage from the LMM to the PMM aquifers of greater extent than hitherto supposed.

3. Specific yield values for the PMM are more likely to be in the range 25-35%.

The mathematical groundwater models have been constructed using the static water levels observed over the study area, together with the aquifer parameters derived from pumping tests carried out at nine locations. Initially, quasi-steady state conditions were assumed and the steady-state model was calibrated by adjusting regional aquifer parameters on the model until the performance of the model matched closely the water level conditions in the PMM aquifer.

Boundary inflows and outflows were calculated on the basis of the estimated transmissibilities and piezometric gradients in the PMM aquifer. Minor leakage from the LMM to the PMM was postulated in a 60km strip to the north of the Oasis Calanscio Field. The model base assumed was that of the original base of the PMM and this is also shown on the four geological cross-sections.

Departures from the assumed boundary conditions relate to the revision of the base of the PMM and the re-analysis of the basic flow patterns which indicate more extensive leakage from the LMM to the PMM than was hitherto supposed. Particular details are as follows:-

(a) Departures concerning water levels in the model PMM which have been correlated with levels in the LMM to the north of 29° 00' latitude and east of 20° 45'. Over much of this area, the two piezometric surfaces are probably co-incident although some significant deviations may occur in a rather critical area to the west and north of Occidental A Field in which information on the PMM head levels is limited.

(b) Departures relating to errors in the assumed position of the PMM base. In the southern Phase 1 Area, the model base is little different from the true base of the PMM. Some additional leakage may be postualted in the southeast corner where adjacent boundary horizons are permeable but head differentials are not of a high order. Boundary inflows during steady-state conditions are therefore unlikely to require adjustment. During transient conditions, leakage could significantly increase if a bigger differential should develop. The region is remote from proposed abstraction fields and the factor is therefore not one for immediate consideration. Any well field in this area would also withdraw water directly from the LMM as well as the PMM.

The situation is considerably different in the north where the base of the PMM has been markedly adjusted following the amendment to the stratigraphic succession. The transmissibilities in the PMM are clearly less than the model values. At C1-95, for instance, transmissibility of the PMM is unlikely to exceed 650 m^2/day, (section 2.2.3.11) whereas the model value is 1200 m^2/day. At A1-LP3C, transmissibility of the PMM is zero since the water table occurs below the PMM boundary, whereas the model value is 400 m^2/day. The two aquifers are continuous in this northern area and in a sense the higher transmissibilities shown by the model seem realistic but not perhaps when considered in relation to adjustment solely for the inflow from the PMM to the south unless inflow from the shallow LMM can be considered of negligible magnitude. Information is not extensive but there are indications of a low transmissibility of the shallow LMM in the significant area around latitude 29° 00'.

Inflow will also need to include localised leakage from the LMM to the PMM, as well as flow within the LMM. At JF, (Table 17) to the immediate south of an area of probable leakage, model transmissibility is appreciably lower than the aquifer analysis value. An explanation may be found in the reduction of gradient in consequence of upward leakage, with an apparent reduction of T implied by a closed system.

The detailed effects of these modifications to the systems boundaries would require model restructuring to evaluate accurately but some qualitative considerations may be noted. The implied changes occur generally northwards of the central Phase 1 Area where all proposed well fields are located. The commonly close correlation of model and aquifer analysis transmissibilities (Table 17) for the central Phase 1 Area indicate the model's validity in this area and in consequence the basic conclusions of the transient analysis are confirmed for the periods in which the cones of depression do not extend significantly to more questionable areas to north and south. Geological features in the LMM indicate little likelihood of upward leakage in the central Phase 1 Area, even with increased head differentials which would follow upon development of the PMM. In any case water quality in the shallow confined LMM is, as already noted, of comparable quality. Leakage effects would therefore be beneficial with reduced drawdowns.

Significant deviations from predicted drawdowns are however more likely to occur with well fields actually located in the more northerly or southerly areas referred to, or when the cone of depression from a centrally located well field attains these locations. The effect will be towards reduction in predicted drawdowns.

2. 5. 2. 1. Discussion of results: Schemes A and B.

The results of the development schemes modelled and discussed in the Interim Report can now be assessed more fully. Development Schemes A and B were modelled assuming unconfined conditions and a specific yield of 0. 1. For Scheme A, the predicted high drawdowns are essentially localised in the well field vicinity in the central Phase 1. For Scheme B, predicted drawdowns to the north of 29° latitude and in the southern Phase 1 Area are either small or even after 100 years, attain locally only 2/4 metres. The basic conclusions can therefore be reaffirmed that of the two schemes, only B (Figure 21) appears practicable with predicted interference drawdowns in the well field area of up to 20 metres within 50 years.

Deviations from these predictions on account of increased leakage or higher specific yield will be towards reductions in drawdowns. The former effect is not likely to be of a high order in view of the central location of the well fields, but the latter could have considerable significance. The excessive drawdowns in scheme A will be reduced although it is still unlikely that they would be within design limits for a 25 year period. For scheme B, incorporating a specific yield of 0. 25, interference drawdowns after 50 years would be halved to about 10 metres. Adding a 20 metres pumping drawdown for 60 litre/sec pumping wells, the maximum drawdown would be of the order of 30m which is adequately within design limits.

2. 5. 2. 2. Tipton and Kalmbach well field: Scheme C.

The proposed Tipton and Kalmbach well field is shown in Figure 1 of Appendix 2. The 100 wells spaced approximately one km apart are disposed in three lines converging northwards to a point from which aqueducts will carry water to the proposed irrigation areas to the south of Augila Oasis. Total design abstraction is 345, 600 m^3/day with the wells being pumped at 60 litres/sec. Supply is estimated to be sufficient to irrigate 7000 hectares.

The results of the IGS modelling are shown in Figures 2-10 inclusive of Appendix 2. The basic IGS model was utilised which assumes unconfined response and a specific yield of 0. 15. It may be seen from Figure 10 that interference drawdowns of the order of 36m are predicted to occur locally in the well field area after 50 years to which must be added a pumping drawdown of 20 metres based upon an assumed specific capacity of 3 litres/sec/metre. These predicted values are excessive when considered in relation to screen design length, and it would be advisable to consider various methods to reduce the interference drawdowns. Obvious methods include a reduction in discharge or an increased well spacing. Phased development of the well field is recommended with a preliminary phase extending for a sufficient period to permit adequate evaluation of the aquifer's response and to calibrate a predictive model. It is possible that specific yield may be in the range 25/35% which would considerably reduce the predicted drawdowns and permit the proposed well-field configuration.

2. 5. 2. 3. Mathematical model incorporating a clay layer

The long term predictions of the behaviour of the PMM aquifer made in the earlier study were based upon a mathematical groundwater model incorporating a totally unconfined aquifer with a specific yield of 0. 1 (10%).

It was recognised in the Interim Report that the presence of clay layers could have an effect upon long term drawdowns which might have to be offset by modifications to well design. The aim of the present study has been to construct a mathematical groundwater model incorporating the effective presence of a clay layer over the area of the aquifer of significance to development schemes A and B.

Studies of the occurrence of clay beds within the saturated zone of the PMM aquifer (Benfield 1974) showed that the spacing of borehole

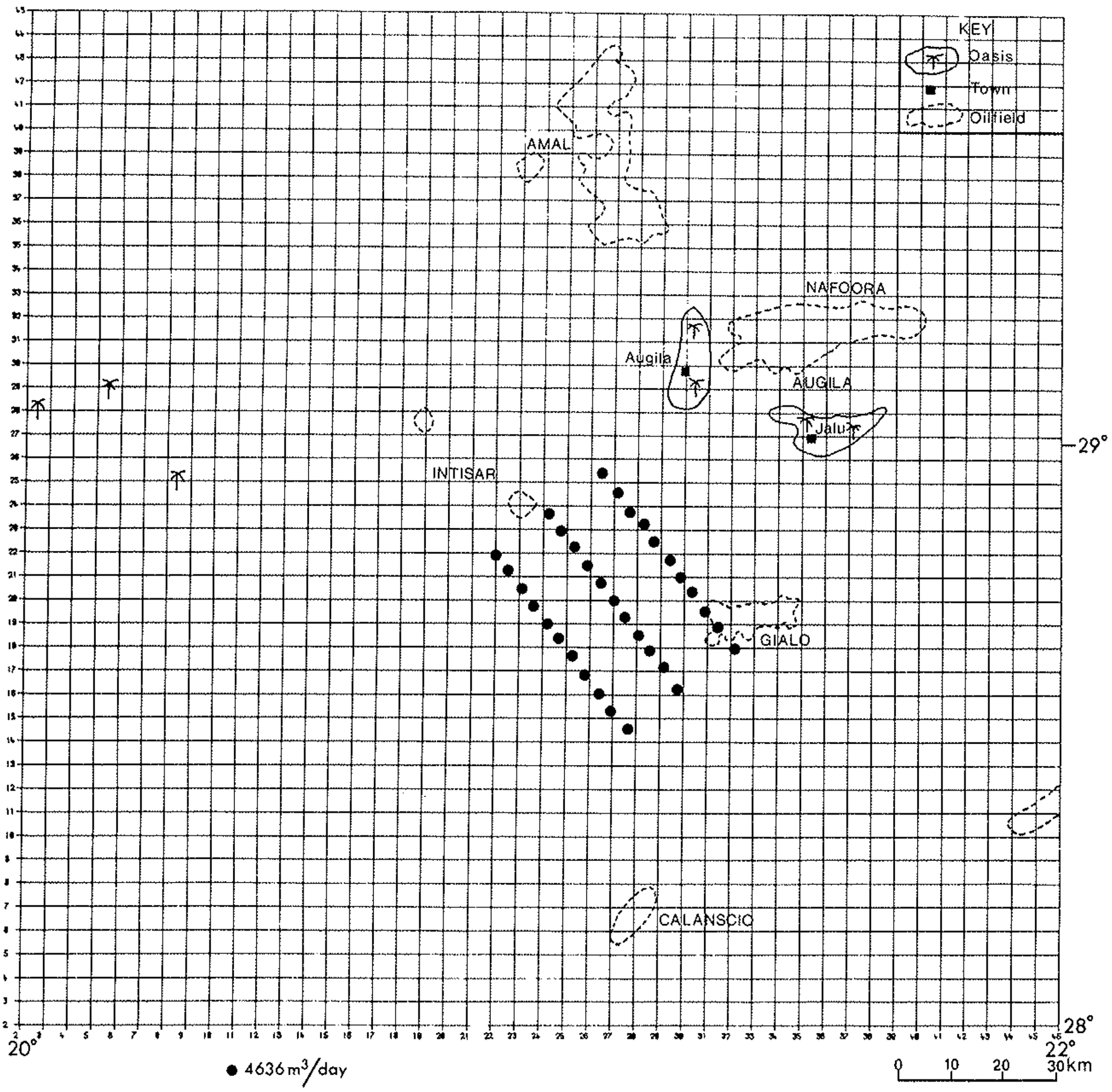

Figure 21. Development Scheme B

sites was too great to yield direct evidence or the lateral extent of any individual clay layer. However, from the hypothesis suggested by the lithological sequence and the grainsize frequency data, deposition appears to have taken place in an alluvial plain environment and the clay beds are likely to extend over distances in the range of 2000 ft to 20 000 ft (600m to 6km). Comparison with one alluvial sequence-the Old Red Sandstone of central England (Allen, 1968) showed good agreement with this range. The clay bed studies further showed that the number of clay beds within the upper 100 feet of the saturated thickness of the PMM aquifer ranged from 1-5 in the borehole sites investigated in the Phase 1 development area.

The present water resource models are based upon a network of nodes or elementary surface areas of the aquifer each a square of side 4.5km. It appears therefore that any clay layer does not extend significantly beyond one or two of the elementary units.

Implementation of development scheme B is likely to lead to significant drawdowns over an area of approximately 50 km x 50km in the long term. The likely extent of an individual clay layer is relatively small compared to the size of this development area and therefore flow around clay layers is probable. Nevertheless the possibility of clay layers extending over larger areas and influencing the regional drawdowns needs to be considered.

The construction of a fully three dimensional transient flow model for a non-uniform aquifer such as the PMM of Jalu-Tazerbo is precluded at present with available computers even if adequate 3-D permeability data were available. Nevertheless, a two layered approach is feasible with the layers separated by less permeable material (clay layer) for which permeabilities may be estimated from pumping test analysis.

As referred to above firm evidence is unavailable on the extent of individual clay layers within the PMM aquifer. Therefore an idealized approach has been taken to the presence of a single layer of this type within the aquifer. The aquifer has been considered to be divided into parts (upper and lower) connected by a layer of which the vertical permeability may be varied from node to node.

2.5.2.3.1. Description of the layered aquifer model

The partial differential equation describing transient two-dimensional flow in an aquifer is:-

$$\frac{\partial}{\partial x}\left(Kh\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kh\frac{\partial H}{\partial y}\right)=S\frac{\partial H}{\partial y}+Q \qquad (1)$$

where

K = horizontal permeability
h = saturated thickness of aquifer
H = potential referred to a datum
S = storage coefficient
Q = abstraction or negative inflow/unit area
x, y space coordinates
t time

It is necessary to re write equation (1) in finite difference form relating to the water balance at a series of elements of the aquifer in order to obtain a solution with a digital computer.

The Phase 1 area of Jalu-Tazerbo Project has been divided into the same network of nodes (small basic elements of surface area) as the earlier models. This network together with associated grid references is shown in Figure 22. The grid references of the boundaries of all maps and lineprinter charts in this report are as follows. (line printer charts are in Appendix 1).

East 2 and 46
North 2 and 45

Grid references East 1 and 47 and North 1 and 46 represent dummy nodes outside the Phase 1 area and are used solely to aid the computation process by defining precise boundary conditions.

Each node represents a small square area of 4.5 km side, the grid reference referring to the centre of the square. For practical purposes water levels may be considered to refer to the centre of the node i.e. the grid reference. Flows and quantities of water are considered to be distributed uniformly over the whole of a particular node. The complete area of the Phase 1 map covers a network 45 nodes east by 44 nodes north. Each node was assigned a value of nodal type index JG, according to whether it was within the aquifer or outside. In those areas where the base of the PMM aquifer intersected the water table, i.e. the western boundary of the aquifer, nodes were considered to be within the aquifer if the centre of the node square was East of the aquifer boundary.

Both the Upper and Lower aquifers were divided into the same network of nodes. Corresponding nodes in the Upper and Lower aquifers were considered to be connected by a layer of material nominally 3 metres thick, a typical

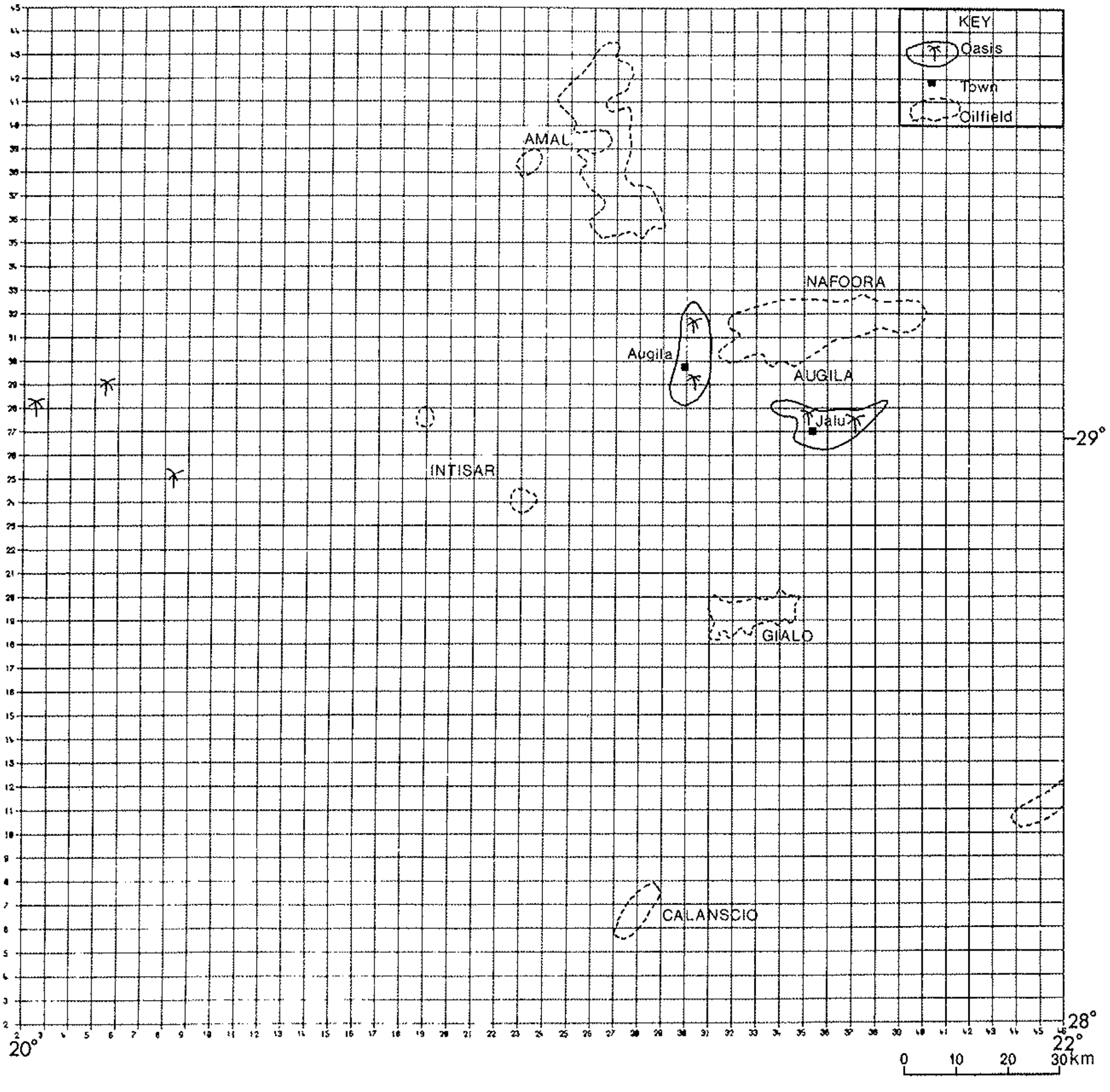

Figure 22. The network of nodes and grid references of centres

thickness of one of the observed clay layers. The cross-sectional area of this connecting layer was taken to be the same as the area of a node i. e. 4. 5. km x 4. 5. km (2020 hectares) and the flow of water was considered to be vertical within this layer. Storage of water within the layer was considered to be constant. The location of the connecting layer between the Upper and Lower aquifers was taken to be at 18 meters over datum - a reasonably typical figure based upon the position of clay layers in the proposed development area. The extent of the simulated clay layer is shown in Figure 23. It covers the area defined by grid references 21 East, 32 East, 15 North, 24 North and is approximately 54 kms x 45 kms. Within this region the vertical permeability of the connecting layer was set initially to 0. 007 m/day which was an estimate based upon the analysis of the pumping tests using a leaky confined aquifer technique. Subsequently a second investigation was carried out setting the vertical permeability of the clay layer to 0. 001 m/day. Outside the area of the simulated clay layer, the vertical permeability of the connecting layer was set to 30. 0 m/day, a value sufficient to ensure a high degree of communication between the upper and lower aquifers and low vertical gradients between the aquifers.

Thus a clay layer of considerable horizontal extent was simulated over the development area in order to test the effect upon predictions of long term drawdowns. The simulated clay layer was not extended over the whole aquifer as it was considered that to do so would not result in a realistic simulation particularly near boundaries where the Lower and Upper aquifers might be "pinched out".

Previous models of this aquifer have considered the storage conditions to be unconfined with a specific yield of 0. 1 (10%). In the present model the Upper aquifer was assigned a specific yield (unconfined) of 0. 1 (10%) and the Lower a storage coefficient (confined) of 10^{-4} (0. 01%). When the water table was lowered beneath the connecting layer so that conditions in the lower aquifer became unconfined the specific yield was adjusted automatically to 0. 1 (10%) and flow through the connecting layer was terminated.

The starting water levels for this transient flow study were the same as those of the steady state model described in the Interim Report. These steady state water levels correspond closely with the observed water levels in the field consequent upon the calibration of the steady state model. Steady state starting water levels will not be influenced by changes in the storage coefficients/specific yields. The horizontal permeabilities and boundary flows remain the same as estimated during the calibration of the steady state model.

The development scheme simulated on the modified model was scheme B (Figure21). This scheme consists of 33 abstraction wells each pumping 1070 U. S. gals/minute (4636 m^3/day) and spaced in 3 equal rows. The spacing between rows is 12 km and between wells is 4 km. The total production is therefore 152000 m^3/day. This scheme was simulated on the model by abstraction at the following nodes:

Grid - Ref of Node	Abstraction m^3/day
22/22	4636
24/20	4636
24/19	4636
26/17	4636
28/15	4636
24/24	4636
25/23	4636
25/22	4636
27/20	4636
29/18	4636
29/17	4636
30/16	4636
26/25	4636
28/23	4636
30/21	4636
30/20	4636
32/18	4636
23/21	9272
25/18	9272
27/16	9272
26/21	9272
28/19	9272
27/24	9272
29/22	9272
31/19	9272

These abstractions were applied to the Lower aquifer. Nodes below 23/21 in the table cover two abstraction wells at the rate of 4636 m^3/day each. Provision was made for either abstraction or boundary flow to take place from the Upper aquifer in the absence of the Lower aquifer.

Water balance equations were set up for each node in turn at a series of time steps using values of water levels between adjacent nodes to calculate the gradients and transmissibilities to compute flow rates. Transmissibility was computed from the product of saturated thickness which varied with time and permeability. Flow components between the Upper and Lower aquifer at each node were determined from the head difference, vertical permeability, thickness and area of the connecting layer. Change of storage

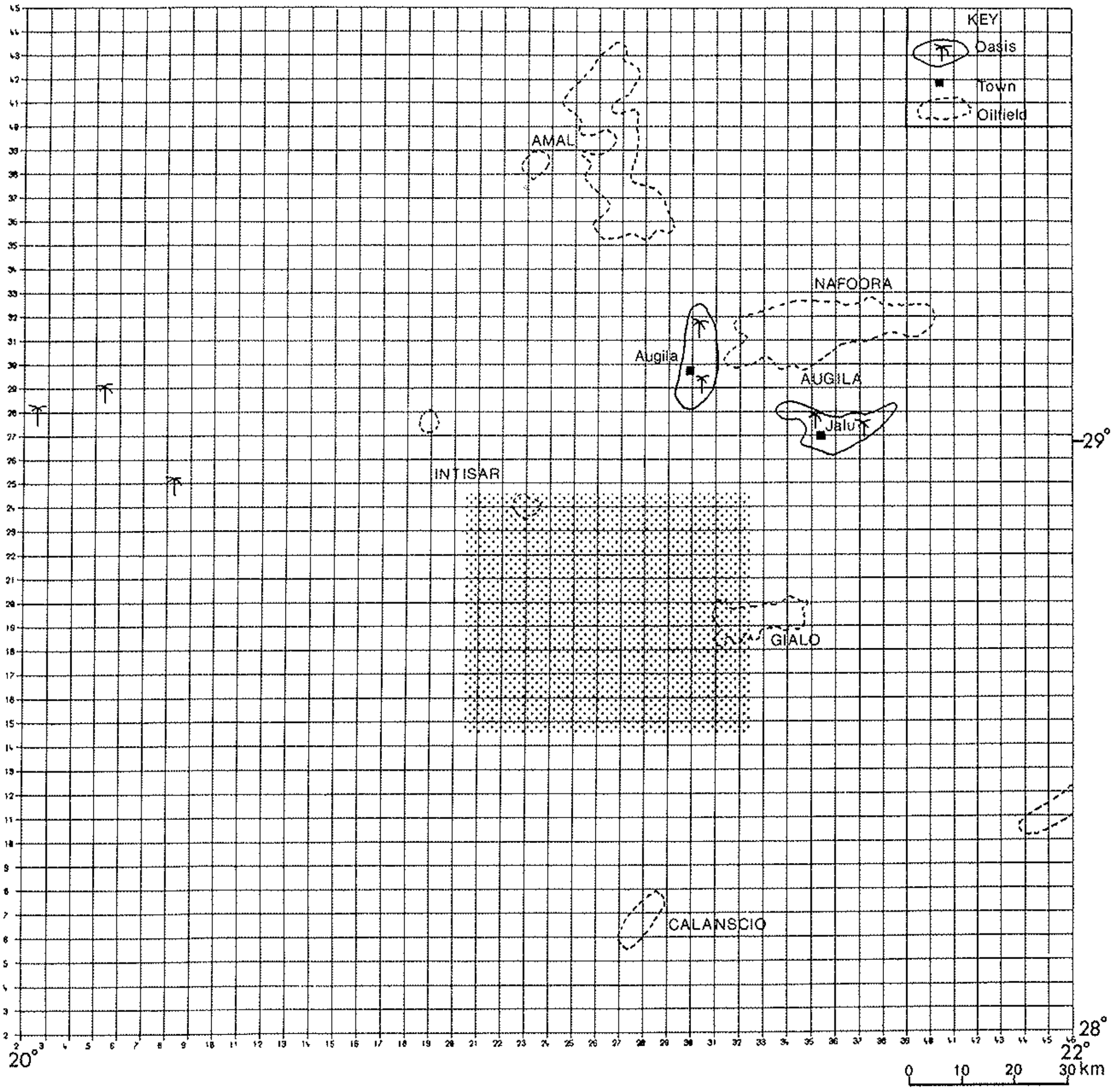

Figure 23. Extent of the simulated clay layer (hatched)

in the Upper and Lower aquifers was related to the change in head of the stored water and the appropriate specific yield/storage coefficient. The various components of the water balance are shown diagrammatically in Figure 24.

In Figure 24, the flow rates are specified at the t + Δt level in the westerly, southerly and vertical directions and at the t level for the northerly and easterly directions. The water balance equations are solved at each node in turn, scanning from the SW corner to the NE corner. For the subsequent time step, the flow rates are specified at the t + Δt level in the northerly, easterly and vertical directions and at the t level for the southerly and westerly directions, scanning from NE to SW. This alternating direction method is repeated throughout the prediction period.

The water balance equations are as follows:-

The complete program was written in FORTRAN computer language and processed upon an IBM 370/195 computer at the Rutherford High Energy Laboratory, Chilton, Didcot, Berks, U.K. All data and computations were in metric units.

The data for the programme consisted of values for the following parameters for each node punched upon 80 column cards:

Easting	IE
Northing	N
Initial Water Level	VG
Horizontal permeability	AKG
Base level of Aquifer	BG
Boundary Flow	BFG
Node Type index	JG

Values of storage coefficients / specific yields, vertical permeabilities and abstractions were incorporated within the main programme.

$$(H_W^{t+\Delta t}-H_O^{t+\Delta t})+T_E(H_E^t-H_O^t)+T_S(H_S^{t+\Delta t}-H_O^{t+\Delta t})+T_N(H_N^t-H_O^t)+T_V(G_O^{t+\Delta t}-H_O^{t+\Delta t}) = \frac{ZA}{\Delta t}(H_O^{t+\Delta t}-H_O^t)+Q_L \quad (2)$$

$$(G^{t+\Delta t}-G_O^{t+\Delta t})+U_E(G_E^t-G_O^t)+U_S(G_S^{t+\Delta t}-G_O^{t+\Delta t})+U_N(G_N^t-G_O^t)+T_V(H_O^{t+\Delta t}-G_O^{t+\Delta t}) = \frac{SA}{\Delta t}(G_O^{t+\Delta t}-G_O^t)+Q_U \quad (3)$$

T and U values are computed as the means of values between adjacent nodes, taking account of saturated thickness and horizontal permeability. H^t and G^t are known at the beginning of each time step. $H_S^{t+\Delta t}$, $G_S^{t+\Delta t}$, $H_W^{t+\Delta t}$, $G_W^{t+\Delta t}$ are known from calculations at previous nodes at the (t+Δt) level.

Thus equations (1) and (2) contain only two unknown values $H_O^{t+\Delta t}$ and $G_O^{t+\Delta t}$ and may be solved for these quantities - the predicted water levels in the Upper and Lower aquifers.

In order to ensure stability it was necessary to begin the computation with a small time step approximately 0.2 days and increase the time step progressively by 25% after each scan of the nodal network. After 2.0 years the time step was constrained to remain constant at 0.5 years. If the water level reached the base of the Lower aquifer the programme terminated with the message "WATER LEVEL REACHED BASE OF LOWER AQUIFER". In the absence of this condition the predictions were continued for periods up to 100 years.

A special FORTRAN subroutine TAB was designed to display aquifer information and results rapidly and conveniently upon the lineprinter so that the results of the model could be checked speedily. Values of water levels at certain nodes were printed out in fixed format for each time step for checking purposes. Additionally sets of punched cards were produced by the programme for prediction periods 25 years, 50 years and 100 years. These cards listed Upper and Lower water levels and the corresponding drawdowns.

A series of lineprinter maps is shown in Figures 5-51 (Appendix 1). The horizontal and vertical numerals are east and north grid references. The alphabetic characters on the map are explained by the key which gives the midrange value of the appropriate parameter for the character concerned. Drawdowns are computed as the difference between the initial water levels and the water levels at the time under investigation.

Each character represents the value of the parameter for the node given by the grid reference.

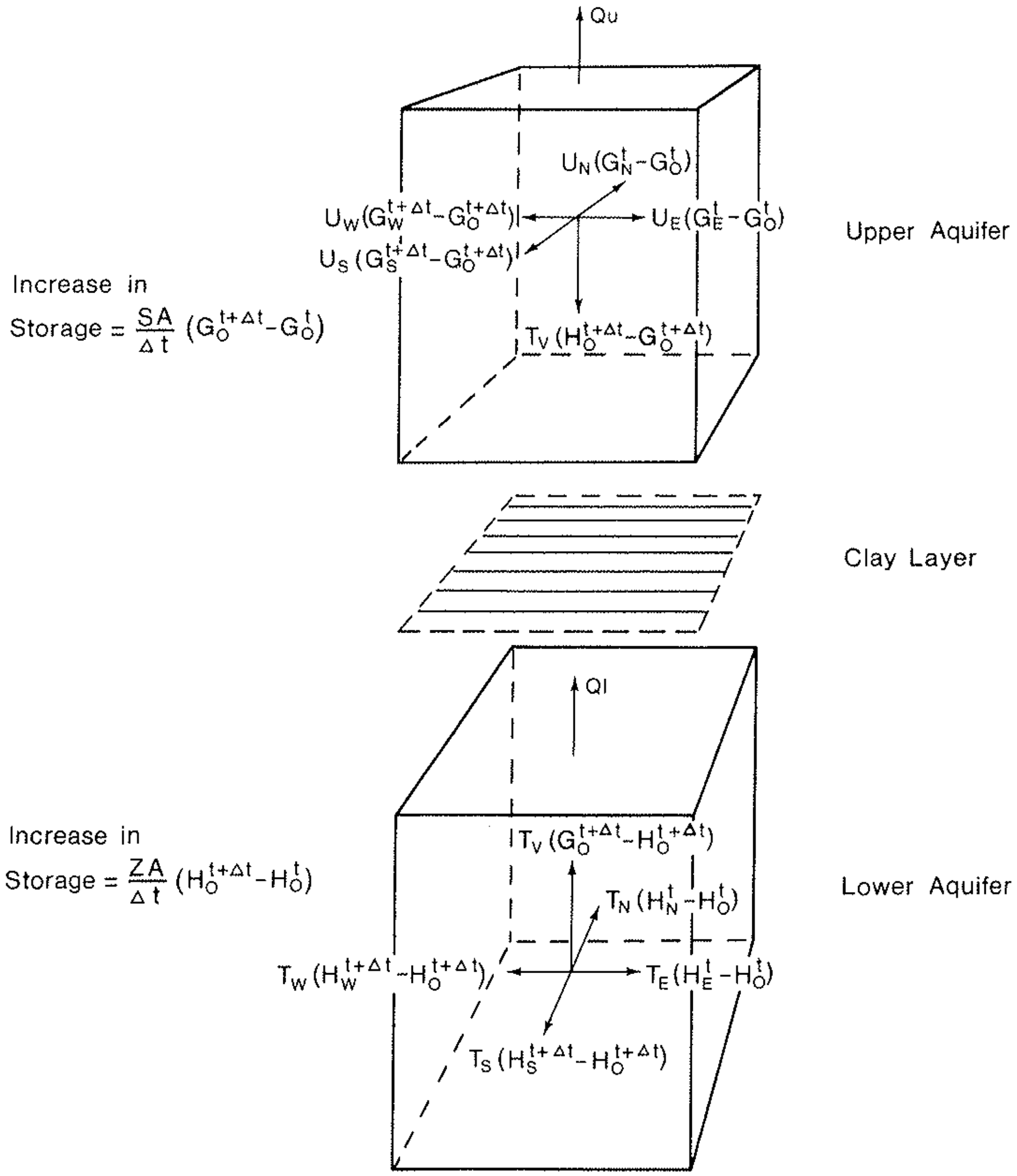

Figure 24. The water balance components

The following notes should be read in conjunction with the lineprinter maps

Figure 5. These initial water levels were those derived from the steady state groundwater model described in the Interim Report. They correspond closely to the rest water levels observed in the field. In general the difference is not greater than about 2 metres. The pattern here is of a positive groundwater gradient towards the north of about 0.35 metres/km.

Figure 6. The base of the aquifer is derived from Map Figure 20c of the Interim Report.

Figure 7. The boundary flows in the figure were those used to calibrate the steady state model. Flow is negative i.e. from the aquifer at the northern boundary and positive i.e. into the aquifer at the southern boundary. Some positive flow takes place into the aquifer from the Miocene aquifer below at the south-western fringe of the model. Symbol M indicates no boundary flow, as on the eastern boundary. Symbol < indicates a node at which abstraction takes place for development Scheme B.

Figure 8. This shows horizontal permeabilities in m/day. These values were derived from the transmissibilities used in the calibration of the steady state model together with the saturated thickness of the aquifer. The typical permeability over the development scheme area is 10 m/day.

Figure 9. This figure is included to show the extent of the simulated clay layer and the value of the vertical permeability used in the model programme. The area of the clay layer is shown by symbol K = 0.007 m/day. Symbol > indicates that the vertical permeability was set to a high value (30 m/day) to ensure good communication between the two aquifers. Symbol D indicates zero vertical permeability i.e. where either the lower or upper aquifer was absent.

Figure 10. Shows the pattern of Lower aquifer water levels 25 years after pumping begins with a specific yield of 0.1 (10%) and vertical permeability of the clay layer at 0.007 m/day.

Figure 11. Shows the corresponding drawdowns being a maximum of about 10 metres in the centre of the development area.

Figures 12 and 13. illustrate the water levels and drawdowns in the Upper aquifer after 25 years.

Figures 14 -17. show water levels and drawdowns in both aquifers after 50 years when drawdowns have reached the order of 16 metres in both aquifers.

Figures 18-21. show water levels and drawdowns; in both aquifers after 100 years when drawdowns have reached about 24 metres in the lower aquifer.

Figures 22 -33. show the water levels and draw-

Fig. 24.

G and H refer to piezometric levels in the Upper and Lower aquifers respectively Lower suffixes ONSWE refer to central, northern, southern, western and eastern nodes.

Upper suffixes t, $t + \Delta t$ refer to time levels at beginning and end of time step Δt.

U_N, U_S, U_W, U_E, are mean values of transmissibility between adjacent nodes in Upper aquifer.

T_N, T_S, T_W, T_E are mean values of transmissibility between adjacent nodes in Lower aquifer.

T_v is equivalent transmissibility between Upper and Lower aquifers.

A is the area of a node

Q_u is abstraction at the central node from the Upper aquifer

Q_1 is abstraction at the central node from the Lower aquifer

S is the specific yield in the Upper aquifer

Z is the storage coefficient in the Lower aquifer.

downs in both aquifers for version b of the programme which simulates a vertical permeability of 0.001 m/day for the clay layer.

Figures 34 - 45. show the water levels and drawdowns in both aquifers for version c of the programme, which simulates a vertical permeability of 0.007 m/day and a specific yield of 0.25 (25%).

Figures 46 and 47 show the predicted water levels and drawdowns after 25 years for the single aquifer model described in the Interim Report.

Figures 48 - 51. show the water levels and drawdowns for the single aquifer model after 50 years and 100 years.

Figure 53. is an overlay map to act as a key to the lineprinter maps. Note that standard lineprinter spacings cause a slight difference in horizontal and vertical sacales on these maps.

2.5.2.3.2. Discussion of results

The transient flow groundwater model was processed three times using the following sets of parameters:

Version	Abstraction Scheme	Specific Yield of Water Table Aquifer	Vertical Permeability of Clay Layer m/day
a)	B	0.1	0.007
b)	B	0.1	0.001
c)	B	0.25	0.007

Version a) simulated the most probable distribution of parameters for the clay layer.

Version b) was a rather more extreme case with greater vertical impedance between the two aquifers.

Version c) was investigated to study the effect upon long term drawdowns of a specific yield of 0.25. It is possible that such values may be attained in the PMM aquifer.

The results of these three predictive versions of the model are readily examined in Figures 10 - 45. As a comparison, the results of the single aquifer model described in the Interim Report are shown in Figures 46 - 51. Lineprinter maps are included for prediction after 25, 50 and 100 years in each case.

It should be particularly noted that predicted water levels and drawdowns in the lineprinter maps in this report refer to regional effects and are average values over the area of a node. The most significant feature of the results of versions a and b is the similarity of the drawdowns in the Lower and Upper aquifers at all times. See for example Figures 15 and 17, which show drawdowns in the Lower and Upper aquifers respectively after 50 years. Highest predicted drawdowns are of the order of 16 metres in both aquifers. In this case the vertical permeability of the clay layer was 0.007 m/day.

When the vertical permeability of the clay layer was reduced to 0.001 m/day as in version b, the water level differential between the two aquifers increased slightly but the drawdowns were still of the same order (see Figures 27 and 29). Drawdowns in version b for the Lower aquifer were slightly greater than in case a.

Figure 49 shows drawdowns predicted for the single aquifer model and these are in close agreement with those of Figure 15 and 27 for the Lower aquifer in cases a and b.

These results indicate that the presence of an extensive clay layer with the properties estimated from the pumping test analyses is not likely to have a significant effect upon regional drawdowns due to development Scheme B.

The assumption of water table conditions on a regional basis therefore appears to be a valid concept in this case.

Version c of the model indicates that long term drawdowns of the water table are considerably less for a specific yield condition of 0.25. Maximum drawdown with a specific yield of 0.25 are of the order of 8 metres after 50 years compared with 16 metres after 50 years if the specific yield is 0.1. The corresponding drawdowns for 100 years are 14 metres (S = 0.25) and 24 metres (S = 0.1).

The detailed studies by Benfield (1974) showed that clay layers are always present in the PMM sequence and it may be considered whether restricting the model clay layer to the main well field area rather than over the region as a whole would have any significant effects. Drawdowns after 25 years (Figure 11, Appendix 2) show that the cone of depression has barely extended beyond the model layer and that drawdowns in the two aquifer subsections differ little from the single aquifer case. It follows from this that little effect is to be expected by extending the clay layer, assuming other conditions are unchanged.

The vertical permeability range 0.001/0.007 m/day is based upon the results of pumping test analysis and accords with the general range for non-indurated over bank alluvial deposits (section 2. 2. 4. 2). The relatively high value in comparison with general permeabilities of marine clay may be related to limited extent of the clay horizons or to sandy material contained within the clay layer. The low gamma values of the PMM clays compared with those of clays from the Miocene and older formations provides some confirmation of this supposition. Extreme values of significantly lower permeability (0. 0007 m/day) were obtained in two cases and such a reduction might significantly increase predicted drawdowns. It will be important therefore during phased well field development to obtain confirmatory evidence on this matter.

The thickness of 3 m used in the model corresponds to a typical individual layer whereas it would have been more appropriate to have used the total thickness found in the upper aquifer levels above probable screen level. These are within the general range 5-10m. However in noting the small change in effect by decreasing permeability from . 007 to . 001, it is unlikely that increasing the thickness by a factor of 2 or 3 would make a significant difference.

3. CONCLUDING REMARKS AND RECOMMENDATIONS

Two aquifer systems occur in the Phase 1 Area, one a single, relatively thin and uniform sand sequence of Post-Middle Miocene age, much of which contains fresh water, and a second, within Lower and Middle Miocene and Oligocene Formations, a multiple sequence of variable lithology and water quality. The contained water in both aquifer systems is fossil. Thus there is no current recharge as a whole but interaction between the systems occurs.

3.1. LMM and Oligocene aquifers

Information on the LMM and Oligocene aquifers is largely qualitative. Based on general considerations of lithology and water quality, the most favourable locations for development for the shallow LMM are in the north and west of the Phase 1 Area; for the LMM generally and the Oligocene development of the resources would probably have to be restricted by water quality considerations to the southern Phase 1 Area.

Resources in the northern Phase 1 Area are likely to be limited but the location may increase the significance in relation to their potential for supplying coastal areas. Resources in the south are likely to be more extensive. Except in the north, the surface terrain overlying these favourable locations is generally unsuitable for mechanised irrigation. For these reasons, resources of these aquifers are more likely to be considered for pumping to other areas, either for town supply in coastal areas, or to more suitable locations for irrigation.

Prior to any development, test drilling will clearly be required and it is not possible at this stage to formulate specific projects incorporating defined well field. However in relation to coastal supplies, the aquifer system does lend itself to phased development, commencing in the north where resources are limited and extending abstraction to the south, as and when required. On that basis supplies are assured and abstraction of moderate proportions could probably be commenced quite quickly. One final note of caution must be made. The shallow LMM is the northern Phase 1 Area is essentially continuous with the PMM aquifer and in consequence any development will relate to both aquifers. The consideration may be of importance when defining priorities for development of resources.

3.2. PMM aquifer

The PMM is a relatively thin aquifer with saturated thickness and transmissibility greatest in the central and east to south-east Phase 1 Area. Water of best quality occurs in the central Phase 1 with deterioration to the east. Deterioration probably occurs in the far north also but information is lacking. In any case, the reduction of the saturated thickness reduces the potential resources in that direction.

The PMM aquifer is in continuity with permeable formations of the LMM in the more northerly and southerly Phase 1 Areas and there is no significant head differential between the two aquifers in these locations. In the central Phase 1 Area, a significant head differential does exist with the LMM at a higher level. Areas of probable leakage appear to be localised in the vicinity of the PMM/LMM boundary. The occurrence is probably more a matter of significance in evaluating long-term aquifer performance since water quality in the shallow LMM appears to be comparable to that in the PMM in these locations.

The PMM responds during short-term abstraction as a leaky artesian aquifer due, it is thought, to the presence of thin interbedded clays in the sand sequence. Studies have indicated that on the assumption that the basic parameters relating to clay thickness, occurrence and permeability are correct, the long term response will be little different to a uniform unconfined aquifer. The clay occurrence has been modelled as an idealised case which is thought might be effectively equivalent to the actual situation.

A mathematical model of the PMM aquifer has been prepared to evaluate resources in practical terms. The initial assumptions on which the steady-state model was based have been proved inaccurate to some extent in the light of later information. Nonetheless, evidence is available which indicates that the model is essentially valid in the main central Phase 1 Area where all tested well fields are located. Three development schemes have been applied to the transient model which assumes that the aquifer will respond in unconfined fashion with a specific yield of 0.1. The first scheme (A) which models a high density well field abstracting 328 000 m^3/day showed excessive drawdowns which fall below suitable design screen limits within 25 years. The second scheme (B) abstracting 152 000 m^3/day from 33 widely scattered wells showed tolerable drawdowns over 100 years. The third scheme (C) based on a well field designed by Tipton and

Kalmbach for abstracting 345 600 m^3/day with wells disposed in converging lines appeared to have locally excessive drawdowns in relation to design screen length within 50 years using the basic IGS program.

Deviation from the predicted drawdowns are most likely to result from variations in specific yield, from upward leakage from the LMM or as a consequence of significantly lower permeability of the interbedded clay layers. Upward leakage from the LMM in the central Phase 1 Area is not very probable on account of the significant percentage of clay in the shallow LMM. Recent data on specific yield based on grain size analysis does indicate the likelihood of higher values than that used in the main model study, with consequent decrease in predicted drawdowns. A significantly lower permeability of the clay layer is a possibility since some low values were obtained in analyses . The uncertainties on these highly significant points do emphasize the need for a phased development with preliminary stages extending for a sufficient period to resolve these uncertainties and to calibrate the predictive model with modifications where necessary. Development should be on a sufficiently flexible scale to permit intensification of well concentration in the later stages dependent on results.

3. 3. General recommendations

Various recommendations concerning development in the Phase 1 Area have been made throughout the text of this report. The most significant aspects are listed below but reference should be made to particular sections within the report for fuller or explanatory details.

3. 3. 1. Well and well-field design

Well field design needs to take account of production requirements in addition to long-term aquifer performance. Data on production wells in the Phase 1 Area indicates an average specific capacity of 3 litres/sec with a well screen of 50m length. This will provide an available drawdown of 30/50m in the central Phase 1 Area of which 20m will be required as pumping drawdown (on the assumption of 60 litres /sec abstraction per well). Because of the fine grain size of much of the component sands, completion with gravel pack is essential. Evidence to date favours an emplaced rather than a pre-pack type. Particular care must be taken to avoid gravel bridging during emplacement as under these circumstances sand pumping is very prone to occur. Particular care is also required to avoid excessive mud penetration during drilling. Adequate development then becomes extremely difficult, expensive and in many cases, impracticable. The correlation that has been obtained between grain size distribution and permeability makes it relatively easy to determine whether development is sufficient. A well efficiency of some 70% is warranted. Slug testing may also assist in this respect. Other important aspects which need to be stressed are the use of flow velocity logs, proper access within the production wells to facilitate measurement of pumping drawdowns, and the need to supply meters on all production wells.

3. 3. 2. Advisability of phased development.

A phased and flexible development cannot be emphasised too strongly. It will permit adequate calibration of predictive models and more efficient well and well-field design.

The data provided by these studies on the hydraulic parameters of the PMM for the overall area require confirmation in the more restricted proposed well-field areas. Transmissibility can best be obtained from controlled aquifer pumping tests but values can also be obtained by sample analysis. The significance of the latter method in relation to ease of obtaining and economy is obvious. It is however recommended that both methods be used initially with varying emphasis and information sought to confirm the latter technique's correlation. Detailed recommendations for the design of short term pumping tests are contained in section 2. 2. 4. 4. and in the Interim Report.

Specific yield is best, obtained using long term abstraction information in association with suitable observation wells. A correlation with grain size variations should be determined if possible to permit readier evaluation of this parameter over extensive areas.

3. 3. 3. Model calibration

The data provided by these studies indicates that the basic model is likely to be adequate for well-fields in the central Phase 1 Area. Confirmation of the basic hydraulic parameters of the main aquifer and the interbedded semi-confining clay layers must be confirmed during the calibration phase. A point of emphasis relates to the transmissibility of the east-central Phase 1 Area where the model values are rather lower than the direct determinations (see J(F1-97) and J(KK1-12) in Table 17). If the model values prove too low, the factor could become of significance in relation to the movement of the more saline water of the eastern Phase 1 area towards centrally located well fields. The development of a chemical model would be desirable which will take those aspects into account.

Modifications to the basic IGS model will be required if development is proposed in the northern or southern Phase 1 Areas, to take account of the interaction and continuity of the PMM and shallow LMM aquifers. Relevant details are discussed in sections 2. 3. and 2. 5. 2.

3. 3. 4. Planning

An overall plan for water resources development in the Phase 1 Area is desirable and would assist efficient development. Even if this is not immediately practicable, general considerations of priorities and future requirements are warranted. Basic data have been provided in this report on which a basic plan could be formulated. Suggestions have been presented for integrated and phased development schemes moving from one location to another depending on available resources and water quality considerations etc. Such schemes do however require careful planning for efficient operation.

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