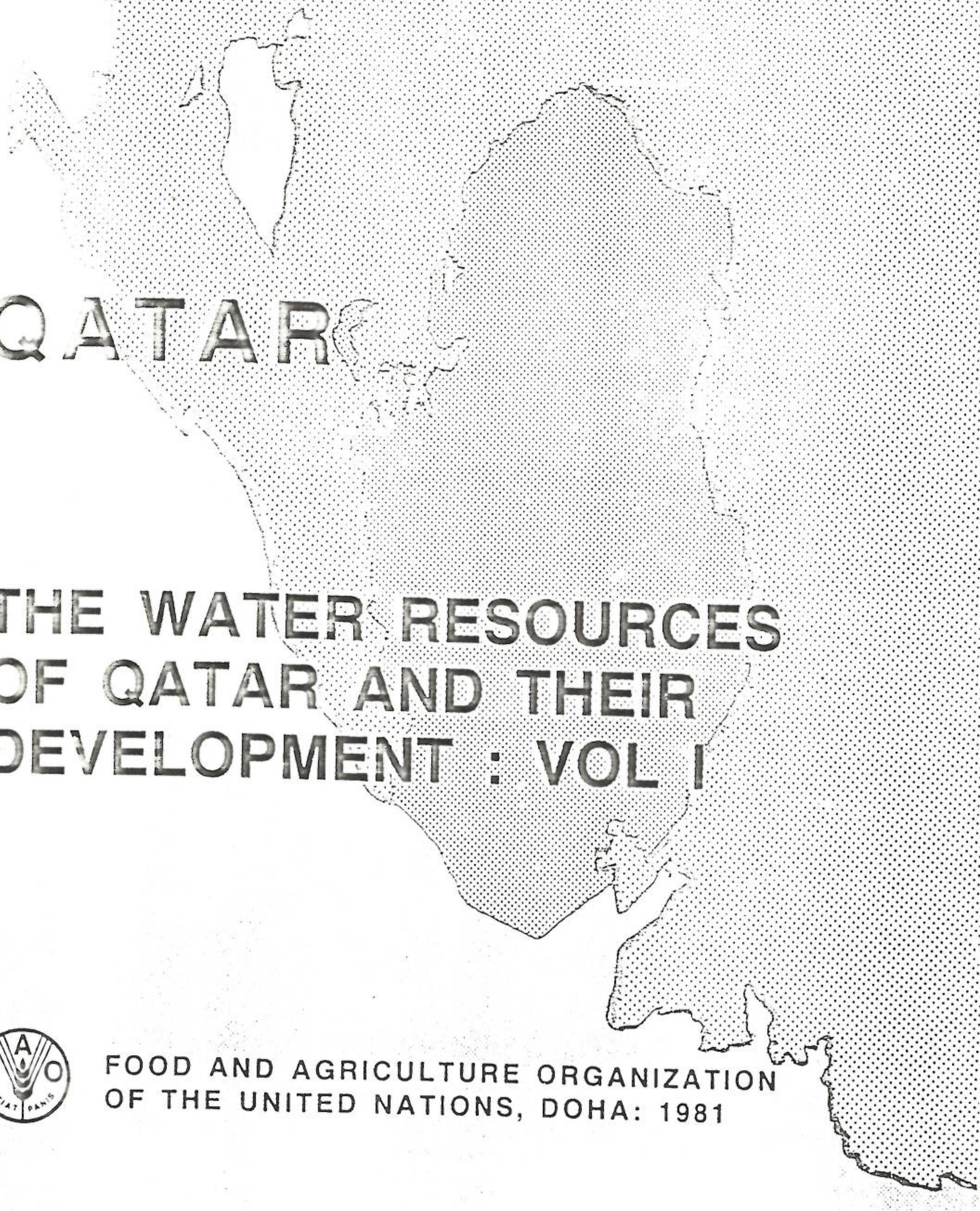
WATER RESOURCES AND AGRICULTURAL DEVELOPMENT PROJECT



QATAR

THE WATER RESOURCES OF QATAR AND THEIR DEVELOPMENT : VOL I

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, DOHA: 1981

NOTE

This technical report is one of a series of six reports completed during the closing stages of the joint Qatar Government/FAO (Funds-in-Trust) Water Resources and Agricultural Development Project and has been approved by FAO for publication at project level.

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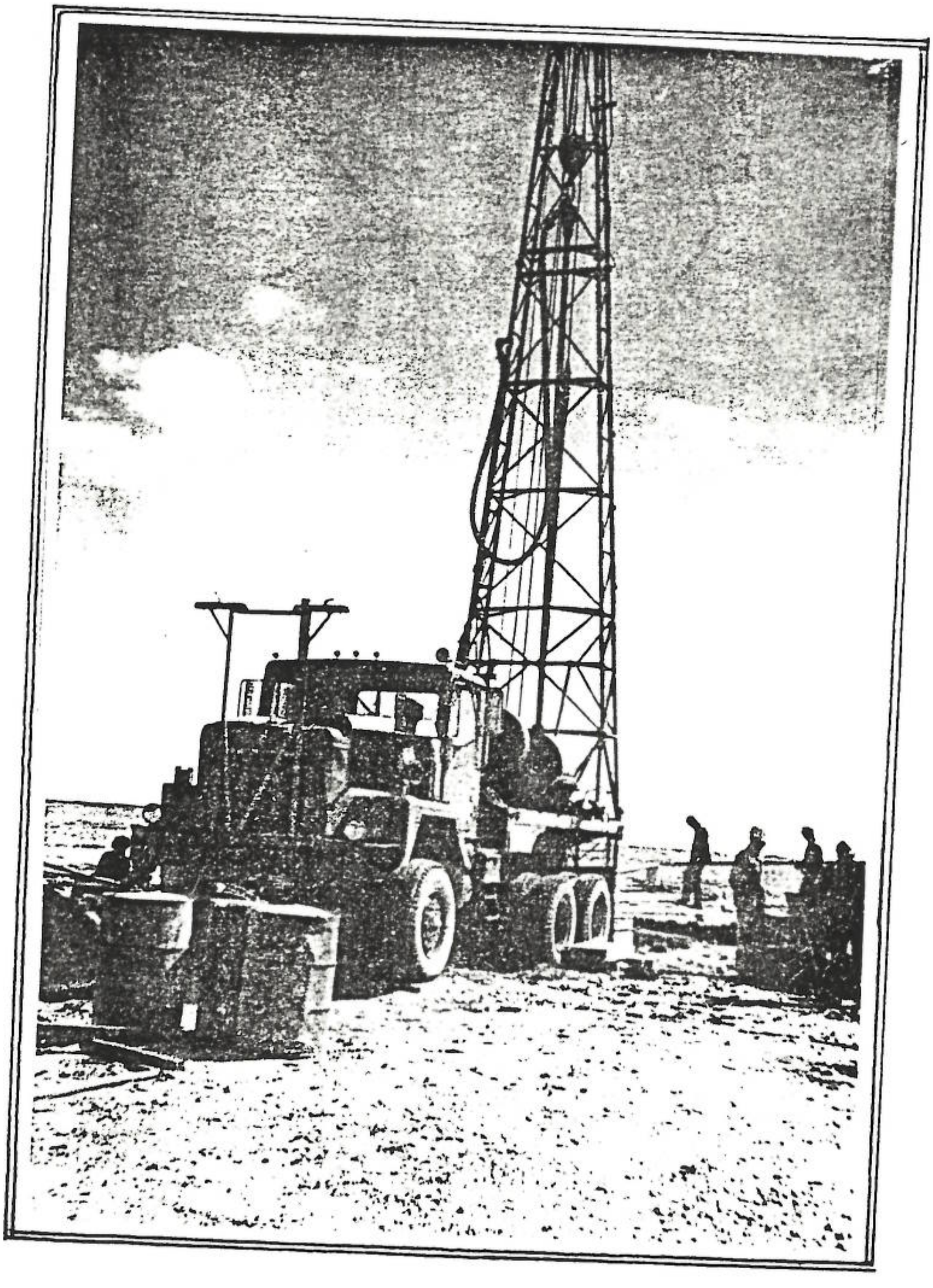
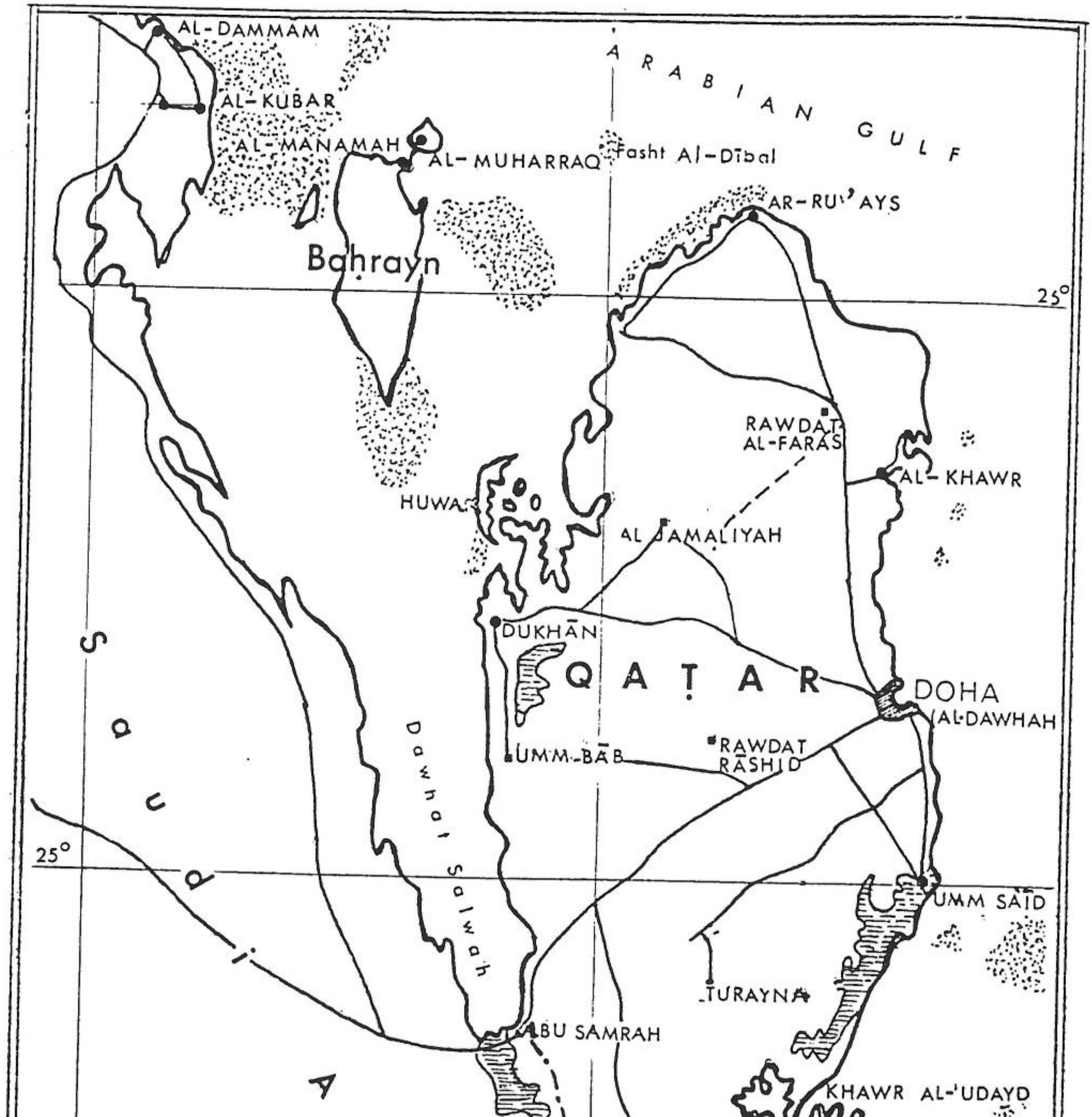
CORRIGENDA

Page	Corrections
XII	Fig. 6.1 occurs on page 6/8
XII	Fig. 8.35 occurs on page 8/46
1/4	Line 7, for 'studies' read 'strides'
2/10	Section 2.2.2, Line 5, for 'of' read 'upon'
3/5	Section 3.1.4, Line 11, for 'complication' read 'compilation'
3/15	Section 3.2.3.1, Line 21, for 'subsidiary' read 'subsiding'
5/9	Section 5.5, Line 1, for 'with' read 'wind'
5/11	Section 5.5, Line 2, for 'may' read 'many'
5/22	Section 5.8.3, Line 14, add 'network' after 'hydro-meteorological' and add 'points of view' after 'distribution'
6/5	Section 6.4.1, Line 3, add 'was made' after 'depressions'
6/6	Section 6.4.2, Line 15, for 'ranges' read 'ranging'
6/6	Section 6.4.2, Line 25, delete last sentence
6/7	Section 6.4.2, Line 8, for 'IX' read 'X'
8/9	Section 8.4.2, Line 4, after 'Isosalinity' add 'Map (Encl. 2). The values range from 500 mg/l in the northern'.......



THE SEARCH FOR WATER



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PREFACE

This report represents the accumulated findings of two successive FAO-assisted projects over the period 1974-81 and is based principally on the work of B.L. Eccleston, FAO Hydrogeologist (1978-81), and J.G. Pike, FAO Project Manager/Water Resources Specialist (1974-81) assisted by Mr I. Harhash, formerly hydrologist with the Qatar Ministry of Electricity and Water. It also contains contributions by a number of persons other than the authors and their work has in most cases been recorded in occasional technical papers or consultants report listed in the biliography.

During the first Project (1974-77) Dr. D.H.Parker served as hydrogeologist for a period of 9 months in 1975/76 and additional hydrogeological advice was provided by FAO Consultants Mr L. Willis Hyde of the Geological Survey of Alabama, (U.S.A.), Mr William Barber and Mr D. Carr both of Raikes and Partners, Rome. Valuable field work in hydrometeorology and hydrology was carried out by Mr B.A.P. Gemmell, FAO consulting hydrometerist, during two winter seasons (1974/75 and 1975/76), by Mr Y. Yurtsevier of the International Atomic Energy Agency on environmental isotope sampling and Mr J. Kirkham who superintended all drilling operations during 1979/80. Specialist advice on cloud seeding was provided by Dr Joanne Simpson of the University of Florida (U.S.A.) and on remote sensing by Dr W. Barrett of Bristol University (U.K). From 1977/78 onward Dr J.W. Lloyd of Birmingham University (U.K.) served as consulting hydrogeologist, provided specialised laboratory services at the Department of Geological Sciences of that University and assisted in the preparation of this report. Similarly, Dr T.R.E. Chidley of the Department of Civil Engineering of the University of Aston in Birmingham (U.K.) provided specialist advice and direct assistance in formulating and developing a computer model of the northern aquifer system and preparing the relevant chapter of this report. Dr Bryan Payne of the IAEA in Vienna provided valuable support as a corresponding consultant in environmental isotopes. Throughout the entire period the work was monitored and assisted by Mr R.G. Thomas, Senior Officer, Land and Water Development Division, FAO, Rome.

The work of the project was jointly executed by FAO and the Ministry of Industry and Agriculture and the Ministry of Electricity and Water of the Government of Qatar who seconded staff to the project. The work of these officials, Sd. Mohammed Fahd Al-Faihani, Head, Water Resources Section (now Director of Agricultural and Water Research Department); Sd. M. Youssef, Computer Specialist, Sd. M. Fauda, Meteorological Assistant, Sd. Salahuddin Nawab Uddin, Well Observer and Junnaid Mahmood, Draughtsman, supported the investigation over an extended period of time. Other government officials also provided direct assistance to field operations. In particular, Mr G.W. Atkinson of the Water Department who gave long and consistent support to the project drilling operations from 1977 onward and worked closely with the project on all matters related to hydrogeological exploration; Mr N.R.G. Walton who provided valuable criticism on geochemical matters during a brief association; Mr D.B.A. McGregor of the State Electricity Department who undertook the frequent repair and calibration of electronic geophysical and meteorological instruments; and Mr H. Channah, Chemist of the Water Department Laboratory who undertook the analysis of all water samples.

The successful completion of project investigations was to a large measure the result of the work of the Project Co-Manager, Mr Michel Farah, who was responsible for the organization of day-to-day activities and for the timely provision of equipment and personnel support. The interest and support of Sd. Ahmed Al-Ma'na, Under Secretary, and Sd. Sultan Al-Kuwari, Director of Agricultural Affairs is gratefully acknowledged.

Thanks are due to Mrs Elizabeth McGregor, FAO Administrative Assistant/Secretary for office organization and many hours of typing shared with Miss M. Ancilla D'Souza and Mr P. Vijay Kumar.

A geological map of Qatar, prepared by Seltrust Engineering on a revised topographic base map by Hunting Technical Services for the Industrial Development Technical Centre (IDTC), accompanies the report with the kind permission of the Director-General of IDTC.

INTRODUCTION

1.1 PROJECT BACKGROUND

Qatar occupies an arid peninsula of 11,610 km^2 which protrudes into the Arabian Gulf as an appendix to the Arabian land-mass. This peninsula is about 180 km along its north-south axis and the east-west width at its widest point is 85 km. Despite Qatar's marked geographical feature, little scientific information existed prior to the initiation of oil exploration in the years immediately preceding the Second World War. Prior to this the country was sparsely settled in the northern and eastern coastal areas by members of various tribal groups, some of whose origins may be traced to the Najd region of Saudi Arabia and others from various other parts of the Arabian Gulf. The permanent settled population at that time is estimated to have been about 25,000 whose main pursuit was fishing and pearling. This population is said to have remained relatively static and with the recession in the pearling industry in the 1930's declined as a result of emiaration to other parts of the Gulf.

The advent of the oil age has completely transformed the socio-economic scene of Qatar. Oil production commenced in 1948 and rose steadily to 13,845 tonnes in 1966 but over the past decade has doubled to a stabilised level of some 500,000 barrels a day. With the raising of posted oil prices at intervals since 1973, annual income from oil production has increased from $ 350 million in that year to a level expected to be $ 5,500 million in 1980. Although the indigenous population has increased at a rate of between 2.5 and 3.0% per annum to a present day total of some 60,000, the total population is now (1980) estimated to be of the order of 265,000.

The life of oil reserves is estimated to be about 35 years at present production levels and production is expected to begin to fall within a decade. However, with the discovery of a vast offshore gas deposit - known as the North-West Dome in 1972 and the recent increase in natural gas prices to conform to equivalent oil prices, the economy of Qatar is expected to be dominated by hydrocarbon production well into the foreseable future. Nonetheless, the Government of Qatar are anxious to diversify the economy to lessen the dependence upon oil and gas and have over the past decade established the nucleus of an industrial base at Umm Said. With the view to broadening the economic base even further, priority is being afforded to agricultural development with the aim of achieving a high measure of self-sufficiency in basic foodstuffs.

Present agricultural production is confined to the seasonal cultivation of vegetable and fruit crops from a small cultivated area which varies from 3000 to 3600 ha out of a total arable area of 29,600 ha. The large amount of water required to maintain present rates of production are however imposing a severe strain on available groundwater resources and it is evident that the availability of good quality groundwater will become a major constraint to development diversification within the next few years. Indeed, as will be shown, groundwater supplies are at present being mined at an accelerating rate and are likely to be exhausted or have deteriorated to an unacceptable quality within the next two decades, and possibly well before oil reserves are finally consumed.

1.2 SUMMARY OF PREVIOUS WORK

Hydro-geological and geological investigations in Qatar were initiated in the early 1930's with the onset of oil exploration surveys. Prior to this only brief reference to the regional geology were published by some early travellers. An early account (Pilgrim, 1908) of the geology of the Arabian Gulf included a brief reference to Halul Island, the present terminal for Qatar's off-shore oil fields. Oil exploration in Qatar included seismic surveys and exploratory drilling and this work required, among other things, adequate water supplies. Unpublished records of the Qatar Petroleum Company (QPC) contain numerous references to the occurence of groundwater and these have provided important, if somewhat limited, data on the steady state groundwater regime of Qatar prior to the onset of pumped extractions at a progressive rate over the past 25 years. Williamson and Pomeyrol (1938) have provided the earliest reliable data on water levels in Qatar in a study oriented towards the provision of water supplies for exploratory drilling operations.

The creation of the Water Department within the Ministry of Electricity and Water in 1954 recognised the rapid economic growth of the country and its consequent demands on freshwater supplies. The first comprehensive study of the hydrogeology of northern Qatar was undertaken by Le Grand Adsco in 1957-59, which included core drilling and resistivity surveys in a number of depressions. At that time only two wellfields were in production, having been constructed by QPC, but with the identification of additional sites by Le Grand Adsco new fields were subsequently developed to provide a water supply to the growing township of Doha (Al-Dawhah), which had previously obtained somewhat meagre supplies by transport from a number of deep caverns (Ar. '<u>dahl</u>, pl. <u>dehūl</u>) of east central Qatar and from wells in the Rayyan area.

With continuing water shortages encountered in the rapidly growing municipality of Doha, government commissioned a new survey of groundwater resources in 1960-61. This survey, undertaken by Ralph M. Parsons Corporation of Los Angeles, recommended exploratory drilling to determine the aquifer potential of the deep middle Cretaceous to Paleocene formations which, in neighbouring Saudi Arabia, were known to contain large groundwater supplies of reasonable quality. As a result of this recommendation (Parsons, 1962) three deep wells were drilled by Amojil in 1963, which showed the deeper aquifers to contain saline water unsuitable for any purpose. The prospects of obtaining potable water from the deeper aquifers in Qatar had in fact been the subject of correspondence between government and QPC in 1961 whereby the latter categorically stated that no such potential existed and drilling records contained abundant evidence in support of that conclusion. The deep exploratory drilling carried out by Amojil in 1963 therefore merely confirmed QPC's conclusion. In a study of the regional hydrogeology of north-eastern Saudi Arabia by Naimi (1965) clear evidence is presented which shows that the salinity of all the Mesozoic - Cainozoic aquifers increases eastwards towards the Qatar peninsula, consistent with the hydraulic gradient and distance from the source of recharge. In 1967-69 Italconsult carried out an extensive hydrogeological survey of eastern Saudi Arabia and Bahrain which further confirmed this earlier conclusion.

The deep drilling carried out by Amojil in 1963 did however reveal that the overlying middle Eocene sediments at Abu Samrah, in the south-western corner of Qatar and close to the Saudi Arabia border, contain brackish groundwater under artesian pressure that could be used for certain limited purposes. Sogreah (1966) carried out an evaluation of water sources for the Doha water supply and provided a number of alternatives whereby municipal water requirements could be met. Among these they recommended that the brackish groundwater at Abu Samrah be piped to Doha and blended (either in its raw state or after partial desalinisation) with distilled sea water. This proposal was not implemented and the requirements of Doha were subsequently met by the construction of additional wellfields in northern Qatar and increasing the capacity of the sea water distillation plant.

The Qatar peninsula forms an integral part of the Arabian peninsula, and the geology of Qatar follows the detailed and well-defined stratigraphy of Saudi Arabia as presented by Powers <u>et al</u> (1966). Geological maps of Qatar on scale of 1:100,000 and 1:200,000 were published in 1970 (Cavelier, 1970) by the Bureau de Recharches Geologigues et Minieres (BRGM) for the

Department of Petroleum Affairs. These maps have provided the geological basis for the current investigation.

1.3 SCOPE OF ACTIVITIES

Prior to the late 1950 agriculture in Qatar was confined to a few farms and date gardens within the environs of Doha and some of the other main centres of the country but from about 1958 onward the number of farms increased steadily to reach a total of over 350 by 1967 and in excess of 500 by 1980. This expansion in agriculture has, however, placed a considerable strain on the existing groundwater resources of the country and as early as 1967, a year in which total abstraction is estimated to have exceeded the normal recharge from rainfall, the Government of Qatar began to view with concern this continued over-exploitation of its groundwater resources. At that time, however, there was very little hydrogeological or other data upon over-exploitation could be made. In late 1971 therefore Government, with the technical assistance of the United Nations Development Programme and the Food and Agriculture Organization of the United Nations (FAO), initiated a project known as 'Hydro-Agricultural Surveys'. This preliminary project was brought to a close in 1973 after having established a hydrometeorological and hydro-geological observation network throughout the country, carried out a geophysical survey and the exploratory drilling of 10 wells, provided an initial quantitative assessment of the hydrological balance of Qatar, completed a soil reconnaissance survey, limited horticultural trials and provided a land classification.

With these basic data as firm foundation, the Ministry of Industry and Agriculture, with the collaboration of the Water Department of the Ministry of Electricity and Water and increased technical assistance by UNDP and FAO, initiated a follow-up project in mid-1974 and known as 'Integrated Water and Land Use'. The objective of this expanded project was to carry out a wide range of studies and investigations arising from the previous project's recommendations aimed at achieving a close integration of the limited groundwater resources with agricultural production, taking into consideration also both present and future possible usage of water for municipal and industrial purposes, and to collect and analyse hydro-agricultural data pertaining to water supply and usage.

Between 1974 and 1977 the project carried out a wide range of observations, investigations, experiments, trials and special studies on both water resources and agriculture. The hydrological and groundwater observational networks were modernized and expanded by the installation of an additional 12 automatic rainfall recorders, bringing the total raingauge network to 32 or a density of one gauge per 332 km^2 and providing Qatar with one of the highest raingauge densities in the Middle East. Twelve automatic water level recorders were also installed, and the well monitoring network expanded to 130 observation wells. Intensified observations of run-off, infiltration and recharge were carried out after heavy rainfall and these data supplemented by the drilling of a further 10 exploratory wells. The occurence and movement of groundwater within Qatar was further evaluated by the introduction of environmental isotope studies, carried out with the collaboration of the International Atomic Energy Agency (IAEA). These studies provided valuable confirmation of the relative age of groundwater, their source and evidence of contamination by salt water intrusion. The boundary of the freshwater aquifer of northern Qatar was accurately defined by a new geophysical survey. The total groundwater extraction rates for domestic and industrial purposes was determined and a renewed agricultural abstraction survey was undertaken. This was later confirmed by an independant sample survey undertaken as part of the agricultural production and farm management survey which included a survey and analysis to determine the cost of water.

At the close of project operations in mid-1977, the Government of Qatar decided to intensify these integrated water resources and agricultural investigations particularly in the light of project results which showed clearly the high potential for agricultural production under improved practices and especially with regard to water conservation. One of the many major conclusions of this phase of investigations was that production on existing land could be increased by some 33% with only half the present amount of irrigation water. This tentative conclusion has clearly pointed the way to implementing the many, but comparatively simple, improved cultural soil and water management practices which will bring about this increased level of water use efficiency. Consequently, a new project, known as 'Water Resources and Agricultural Development' was initiated in July 1977 with the continued assistance of a team of experts under a Fund-in-Trust agreement with FAO.

The objective of this third FAO-assisted project was to intensify investigations in certain areas and to initiate the implementation of proposals and recommendations arising from the former project. With the accumulated experience of some 6 years of prior investigations, this project was able to make significant studies towards concluding major unresolved problems as well as initiating new phases of work and the pioneering of agriculture in the sand dune area of south western Qatar.

In the hydrogeological sector a renewed, but closely supervised drilling programme was carried out and 12 new exploratory wells were drilled. Geophysical logging of wells was undertaken and these data, together with those obtained from additional chemical and isotope analysis enabled the project to modify the previously held concept of a floating freshwater lens to a more comples , two-layered aquifer system in which all previous anomalies and unexplained features may now be reconciled. Based on these additional data a computer based mathematical model of the northern aquifer was devised and is now available for the testing of future aquifer behaviour under simulated or assumed future operating rules.

At the close of the second project - Integrated Water and Land Use - in 1977 a technical report The Water Resources of Qatar and their Development was prepared but it was decided to withhold publication pending the completion of expanded work programmes planned for the third phase project. Although the report was issued on a restricted basis within Government as an interim statement of data and analysis at that time, this present report now incorporates the final results of all data, investigations, studies and analysis performed under the two successive FAO-assisted projects from July 1974 to April 1981.

II
SUMMARY OF
CONCLUSIONS AND RECOMMENDATIONS

2.1 CONCLUSIONS

2.1.1 Introduction

Prior to the late 1950s agriculture in Qatar was confined to a few farms and date gardens within the environs of Doha and some of the other main centres of the country but from about 1958 onward the number of farms increased steadily to reach a total of over 350 by 1967 and in excess of 500 by 1980. This expansion in agriculture has, however, placed a considerable strain on the existing groundwater resources of the country and as early as 1967, a year in which total abstraction is estimated to have exceeded the normal recharge from rainfall, the Government of Qatar began to view with concern this continued over-exploitation of its groundwater resources. At that time, however, there was very little hydrogeological or other data upon which any reliable assessment of the extent of this probable over-exploitation could be made. In late 1971 therefore, government, with the technical assistance of the United Nations Development Programme (UNDP) and the Food and Agriculture Organization of the United Nations (FAO), initiated a project known as '<u>Hydro-Agricultural Resources Surveys</u>' (QAT/71/501). This preliminary project was brought to a close in 1973 and with increased technical assistance by UNDP and FAO, initiated a second phase project in mid-1974 and known as '<u>Integrated Water and Land Use</u>' (QAT/73/007). The objective of this expanded project was to carry out a wide range of studies and investigations arising from the previous project's recommendations aimed at achieving a close integration of the limited groundwater resources with agricultural production, taking into consideration also both present and future possible usage of water for municipal and industrial purposes and to collect and analyse hydro-agricultural data pertaining to water supply and usage.

At the close of project operation in mid-1977, the Government of Qatar decided to further intensify these joint water resources and agricultural investigations particularly in the light of project results which clearly showed the high potential for agricultural production under improved practices and especially with regard to water conservation. Consequently, a third phase project, known as '<u>Water Resources and Agricultural Development</u>' was initiated in July 1977 with the continued assistance of ateam of FAO experts but now under a Fund-in-Trust agreement with the Food and Agriculture Organization of the UN.

In the hydrogeological sector a renewed, but closely supervised, drilling programme was carried out and 12 new exploratory wells were drilled. Geophysical logging of wells was undertaken and these data, together with those obtained from chemical and isotope analysis enabled the project to modify the previously held concept of a floating freshwater lens to a more complex, two-layered aquifer system in which all previous anomalies and unexplained features may now be reconciled. Based on these additional data a computerized mathematical model was devised and is now available for the testing of future aquifer behaviour under simulated or assumed future operating rules.

2.1.2 Soils and Vegetation

The most widespread soils of Qatar are very shallow (10-30 cm) calcareous sandy loams covered with rock debris and overlying a layer of rock fragments on limestone bedrock. These lithosols are of little to no agricultural importance. However, in approximately 1900 separate depressions throughout the country colluvial soils made up of calcareous loam, sandy loam and sandy clay loams have accumulated to depths ranging from 30 cm to 150 cm overlying limestone debris and bedrock. These colluvial deposits are generally of limited areal extent and separated by the lithosols of higher ground and may range in extent from a few hectares to a maximum of 60 ha with a total aggregate extent of 33,493 ha. These depression soils are generally known as <u>rodha</u> (pl. <u>rodat</u> or <u>riyad</u>) and constitute the main agricultural soils of the country. Elsewhere and particularly along the coastal margins, saline soils (sabkha) occur in extensive playas of a total aggregate area of 77,124 ha.

Natural plant growth in Qatar is limited by the seasonal, erratic and variable rainfall and an aerial view of the peninsula will perhaps convince the observer that the country is entirely deviod of vegetation. Six types of plant community have however been recognised and these repeat themselves wherever similar soil and water conditions occur. These community types are : (1) Coastal sabkha (2) coastal sand, (3) rodha depression, (4) sand dune, (5) *Acacia tortillis* and (6) *Zizphus nummularia*. The plant communities of the sabkha and coastal sands are predominantly halophytes. The rodha community type is confined to the colluvium depressions of the same name with mixed and pure stands of *A. tortillis* (samr), *Z. numularia*, (sidr) and *Lycium shawii* (awasij) forming the permanent feature of the landscape and the most outstanding vegetational feature of Qatar. However, there is considerable variation in floristic composition of these depression communities. Those of the northern half of the country have deep soils whereas as one moves southward these have become partially infilled with aeolian sand and exhibit a different vegetational pattern. The distribution of vegetation in depressions has been observed to be closely associated with the two major groundwater provinces of Qatar.

2.1.3. Geology

The Qatar peninsula is a wide anticlinal arch or pericline, with gentle crest and steeper marginal dips and a north-south axis central to the peninsula culminating in the centre of the country. This arch is complicated by the presence of several other more pronounced structures, of which the Dukhan anticline (the main oil bearing structure), the Sawda Nathil dome and the Simsimah dome are apparent. The geological succession is composed of Tertiary limestones and dolomites with interbedded clays, marls and shales covered in places by a series of Quaternary and Recent superficial deposits. The oldest rocks exposed are the limestones of the Rus Formation of lower Eocene age although the most widespread outcrops are the dolomites and crystalline chalky limestones of the Upper Dammam Formation of middle Eocene age. Major faulting has not been observed but the Project geophysical survey, later supported by geomorphological and drilling evidence, has identified a V-shaped facies boundary with an apex at Rawdat Rashid in the centre of the country.

This boundary is of fundamental importance as it marks the division of Qatar into two separate hydrogeological provinces. To the north of this boundary the Rus Formation if of predominantly carbonate facies with only residual deposits of interbedded gypsum. The virtual absence of gypsum is considered to be the result of non-deposition over the broad structural high at the northern end of the Qatar pericline and, also, its removal by dissolution in circulating groundwater derived from recent recharge which has permitted an enhanced access to gypsum beds aided by the significant absence of lower Dammam shales in the centre of the peninsula. In northern Qatar the landscape is made up of an almost contiguous series of depressions with small internal catchments ranging in area from 0.25 to 45 km^2 with irregular bodies of colluvial calcareous soils accumulated in the lowest part or along major drainage courses. In general, the landscape is a deflated and subdued one where the watershed between depressions may sometimes be imperceptable. In southern, central and western Qatar, however, the landscape is entirely different being dominated by low hills formed by outliers of the Neogene formations, barchan sand dunes and extensive areas of flat, eroded limestone peneplain. Wherever depressions resulting from sub-surface erosion occur, however, these are invariably isolated, well-defined and with a crater-like appearance with the floor sometimes as much as 20 meters below the general peneplain surface. The floor of these depressions is usually covered by vegetated aeolian sands.

2.1.4 Climatology

Qatar lies wholly within a torrid sub-region of the northern desert belt, characterised by a scanty rainfall of about 50 mm per annum, high temperatures, hot dry summer winds and, because of its geographical position within the Arabian Gulf, experiences a high relative humidity for the greater part of the year. Climatological data show that the year may be divided into four distinctive climatic seasons of varying length which bear only a general relationship to the main climate seasons of the sub-tropical zone. Period II (November - mid-February) constitutes the main growing season when temperatures range from a daily maximum of 30°C to a minimum of 7°C; Period II (mid-February - mid-May) is marked by rapidly rising temperatures and increased windspeed; Period III (mid-May - July(is characterised by very high daily maximum temperatures of about 42°C and accompanied by strong dessicating north-westerly winds; Period IV (August - October) is marked by the sometimes sudden onset of greatly increased relative humidity and a decrease in wind speed whilst temperatures remain very high. Ope water evaporation ranges from a minimum of less than 2 mm day^{-1} in December to 10 mm day^{-1} in June.

Annual rainfall, deduced from project records and adjusted where necessary shows the deduced annual average rainfall over Qatar for the period 1972-79 to range from 5o to 80 mm. With a coefficient of variation of annual rainfall of the order of 75% the term 'average rainfall' is however apt to meaningless and the isohyetal map presented is merely the mean of annual rainfall totals observed at 15 stations over a 9 year period and provides, at best, an indication of relative amounts of rainfall over the country. From these data the following is concluded;

- The land mass of Qatar, protruding into the Arabian Gulf, appears to be of sufficient extent to provide convection to easterly moving air streams in the winter and more isolated and comparatively intense thunderstorms during the early and late winter. Generally, annual totals tend to be higher in the northern and central areas than along the coasts in winter although during the spring months there is a tendency for thunderstorms to build up over the east coast, possibly as a result of boundary front conditions.

- The maximum rainfall over Qatar occurs as a cell situated in the north central part of the country and coinciding with the main northern recharge area.

- The minimum rainfall is found along the west coast southward from Dukhan which appears to lie in the rain shadow of higher ground to the west in Saudi Arabia. The Dukhan range does not appear to exert an orographic effect.

- Northern Qatar tends to receive an average about 30% more rainfall than southern Qatar.

2.1.5 Hydrology

After moderate to heavy rainfall, usually in excess of 10 mm a run-off from the bare lithosol catchment reaches depressions by a number of incipient drainage channels or directly by sheet overland flow. Recharge to groundwater may take place either directly from rainfall accumulated in hallows over outcrop areas or indirectly by infiltration of run-off ponded within depressions.

From detailed field observations of rainfall, run-off volumes and evaporation and extrapolated by longer term rainfall records, it is concluded that over the period 1962/63 to 1979/80 (18 years) :

- the mean annual recharge over northern Qatar was of the order of 27 Mm^3 with a minimum of 0.50 Mm^3 and a maximum of 85.75 Mm^3, derived from direct recharge equivalent to 2% of the annual rainfall and by indirect recharge equivalent to 10% of annual rainfall.

- In southern Qatar,the mean annual recharge, derived almost entirely from indirect recharge and equivalent to 6% of the annual rainfall, is estimated to have been 14 Mm^3 with a minimum of 0.2 Mm^3 and a maximum of 40 Mm^3.

- Over the whole country the mean annual recharge is estimated to be 41 Mm^3.

A time series analysis of the 18 years deduced recharge shows that the series may be divided into three definite periods :

- 1962/63 to 1968/69 when recharge was 37% above average
- 1969/70 to 1974/75 when recharge was 59% below average
- 1975/76 to 1979/80 when recharge was 17% above average.

While the record is insufficiently long enough to discern any periodicity it is however clear that there is a certain tendency for the persistence of periods of up to 7 years during which time recharge may be above or below average by half an order of magnitude. Whilst storage is sufficient to overcome a 7 year recharge deficit period at present pumping levels, water quality in marginal areas would expect to progressively deteriorate under these conditions.

2.1.6 Geophysics

Two surface geophysical surveys of Qatar were carried out as part of the first and second phase projects respectively. A total of 403 electrical soundings along 21 E-W tranverse profiles covering the entire country were performed. The results of these electrical soundings were analysed to delineate several overlapping hydrogeological conditions; a surface layer of high resistivity (> 100 ohm/m) and a lower water bearing zone with a resistivity range from 0.3 to 130 ohm/m. With a minimum water resistivity of 2.5 ohm.m. corresponding to an EC of 4000 µmho/cm and a total porosity of 35% in the Umm er Radhuma formation, a contour map of the base of the main northern fresh-water body was prepared. A V-shaped boundary, originally defined as that between basically conductive and resistive provinces was found to coincide with a major facies division in the Rus Formation which divides the country into two separate hydrogeological provinces. From later drilling results some re-interpretations of the original hypotheses of the occurence of fresh water in southern Qatar has been carried out.

.1.7 Hydrochemistry

Although hydro-chemical analyses of groundwater in Qatar have been carried out since 1959, the project undertook a detailed sampling and analysis programme to elucidate the hydrochemical evolutionary sequence in support of the hydrogeological analysis. This programme included minor ion and environmental isotope sampling. For this analysis a classification system was devised, designed to include dynamic features of groundwater chemistry and the terms 'sequence' and 'zone' introduced. These terms were adopted to represent, respectively the variation of chemical composition of waters from the recharge to the coastal saline zone, and in describing an area where a certain chemical process is domeinant.

This analysis has confirmed that recharge takes place principally over northern Qatar and through the carbonate facies of the Dammam and Rus Formations to form 'Sequence I' waters. It also takes place over the adjacent sulphate facies area and a number of recharge mounds to form Sequence II waters. Throughout the evolutionary sequence the sulphate waters also have higher calcium, sulphate and magnesium levels indicating that the major source is the gypsum of the Rus Formation.

At a later stage in the evolutionary sequence calcite and dolomite saturation are reached, though the waters continue to dissolve considerable amounts of gypsum and anhydrite whilst the calcite gradually precipitates, causing a loss of calcium and bicarbonate as the sulphate increases. This process of incongruent dissolution of gypsum is believed to occur both as the carbonate waters enter the gypsiferous area and also as they flow to the northern coast. This process causes bicarbonate/TDS ratio to decrease rapidly as the sulphate/TDS ratio increases. Continuing dissolution of gypsum may lead to supersaturation with respect to calcite and dolomite.

In ZONE B total dissolved solids increase and ion exchange process may be inferred with calcium and magnesium ions possibly being exchanged for sodium ions on the surface of clay minerals present in the carbonate as well as the sulphate facies. The almost constant chloride/sulphate ratio in ZONE B then increase towards the value of sea water where it rises to 7. In the range 5000-7000 mg/l TDS, the waters becomes saturated with respect to gypsum when sulphate values of about 2000 to 2400 mg/l are reached, and chloride and sodium increase due to mixing with sea or saline groundwater. Reverse ion exchange waters of higher chloride/sulphate ratio are inferred for ZONE C embracing the entire coastal and immediate hinterland area.

The minor ion chemistry strongly supports the interpretation based on the major ion chemistry. As is to be expected, iodide, strontium and fluoride ion concentrations are significantly higher in the sulphate areas although, with increasing TDS, this difference diminishes to zero. This suggests control mechanisms for minor ions since their concentration remains constant at a high level in the sulphate waters.

IN SW - Qatar, the waters of the Umm er Radhuma and the Alat aquifers cannot be separated chemically from ZONE C/Sequence I waters of the Rus aquifer elsewhere and the only distinguish: parameter was found to be the chloride/sulphate ratio. A long residence period and presumed absence of gypsum or anhydride deposits gave a significantly higher ratio. There is a chemical similarity between the water of the Umm er Radhuma and the Alat aquifers which has previously been taken as evidence of upward leakage of Umm er Radhuma water in the area. Exploratory drilling by the project has however shown that the two aquifers are in fact separated by over 100 m of dry gypsiferous Rus Formation which in this area provides an effective aquiclude. The evidence of environmental isotopes and hydrochemistry from Saudi Arabia has however revealed that upward leakage is taking place from the Umm er Radhuma through 'windows' in the Rus Formation where the evaporites are absent or have been removed by solution.

A detailed sampling programme of groundwater to determine the concentration of the stable isotopes of oxygen and hydrogen, the radioactive isotopes of hydrogen and tritium, and the carbon isotopes carried as dissolved carbonate species in the water, was performed. This reinforced and confirmed the hydrochemical and hydrogeological analysis with a clear distinction in isotopic composition and probable age between modern waters of north-central Qatar and deeper, more saline waters of the Umm er Radhuma and Alat formations of S.W. Qatar. Because of complex mixing age determinations are imprecise and inconclusive and only a generalised division into 'modern' and 'old' waters is possible.

.8 Hydrogeology

In the northern groundwater province there is hydraulic continuity between the Rus Formation and the underlying Umm er Radhuma Formation whereby percolating fresh groundwater has displaced the normally saline water of this aquifer in its upper part. Within this formation, lithological variations and preferential palaeokarstification have given rise to an aquifer of high permeability. Storage upto 100 m at the centre is Qatar's principal reserve of fresh groundwater. Throughout the remainder of the country, except over the positive Dukhan structure, the Rus Formation is principally of sulphate facies. Here the gypsum has not been removed to a major degree due to the very reduced permeability of the gypsum and associated marls and chalky limestones and the presence of overlying Lower Dammam shales which have inhibited recharge. It is believed that fracturing caused by the dolomitization process affecting the exposed Upper Dammam Formation has allowed recharge to gain access to the soluble gypsum of the Rus Formation in discrete localities only creating depressions where limited volumes of useable groundwater are present.

Exploratory drilling, geophysical logging and pump testing has shown that the Rus or upper aquifer, normally composed of chalky limestones, has a relatively low hydraulic transmissivity with values ranging from 20 to 600 m^2/day with isolated values of up to 2700 m^2/day. In contrast the lower, Umm er Radhuma, aquifer exhibits a higher average transmissibility of the order of 3000 m^2/day. In central and southern Qatar usable groundwater is confined to isolated bodies of meteoric water within the Rus Formation underlying large depressions and where there may be access to the underlying, generally saline Umm er Radhuma aquifer. Elsewhere thick deposits of gypsum within the Rus Formation act as an effective aquiclude and where these are encountered this formation is dry. Wells sunk in such areas do not encounter groundwater until the Umm er Radhuma Formation is reached which is normally under a pressure head of some 3 m thus causing substantial sub-artesian effects.

The northern groundwater province is therefore the major source of reasonable quality groundwater in Qatar and is estimated to contain approximately 2500 Mm^3 of freshwater within the two aquifer systems. The safe yield of this aquifer system is estimated to be of the order of 27 $Mm^3 annum^{-1}$. Throughout the remainder of Qatar, except in the extreme south west, groundwater conditions are highly variable with generally poor yields and a higher salinity except in certain favourable areas where meteoric waters have gained access to the Rus and thence to underlying Umm er Radhuma aquifer. While recharge is calculated to be of the order of 14 Mm^3 over this area, for various reasons this cannot be entirely regarded as a usable water resource. In the extreme south western region of the country, the Alat aquifer emanating in Saudi Arabia is estimated to have a safe yield of up to 2 $Mm^3 annum^{-1}$ of variable quality brackish groundwater. The total usable groundwater resources of Qatar are therefore considered to be of the order of 40 Mm^3 annum.

.1.9 Water Quality

The quality of groundwater in Qatar has been regularly monitored since 1971 and is in a process of deterioration under the impact of a increase in the total concentration of dissolved salts from both sea water intrusion and upward migration of deeper, saline groundwater brought about by over-extraction of groundwater over the past decade.

In 1980 the electrical conductivity, expressed in µmhos/cm at 25°C., within the central part of the northern groundwater province ranged from 600 to 850 reflecting recent recharge. Under the impact of pumping along the eastern coast and immediate hinterland of Doha this body of freshwater within the Rus and upper Umm er Radhuma Formations is being invaded by sea water and exhibits EC values in excess of 4000. Groundwater contained within the sulphate facies areas of west, central and southern Qatar shows a highly variable salinity but is everywhere in excess of 2000, more generally of the order of 4000.

The value of the sodium adsorption ratio varies from 5.0 to 8.0 within the main irrigation areas of northern Qatar, the latter value causing a reduction in soil permeability as the calcium ions absorbed on the clay particles are replaced by sodium ions. In areas where gypsum is present, such as in southern Qatar, the effect of sodium excess in irrigation water may be neutralized. Specific ion toxicity is also present in the form of excess concentrations of boron in certain areas, particularly in eastern Qatar. Arising from project agronomic and horticultural investigations crop salinity tolerances have been revised to conform to similar conclusions elsewhere.

Suitable groundwater for domestic consumption is found only in the northern groundwater province containing waters of less than 1500 mg/l of total dossolved solids. Elsewhere, groundwater should not be supplied directly to the consumer and in particular in those areas of central and southern Qatar where magnesium exceeds 30 mg/l and where the sulphate concentration is a excess of 250 mg/l.

O Water Use and Production

The total arable soils in the country cover some 29,600 ha of which, 3,200 ha are at present under irrigation and some 800 ha has already been abandoned as a result of excessive water use and inefficient irrigation. Water is being extracted from the main northern aquifer system at nearly twice the rate of replenishment and the quality is deteriorating at a rate of 5 per cent per annum caused by sea water intrusion and upward diffusion of deeper saline water. To meet increased domestic and commercial demands for water, the fresh groundwater source has been supplemented by distilled sea water since 1964, growing in volume to provide almost 42% of total water consumption in the country by 1980. Total water use in Qatar in 1980 amounted to 125.4 Mm^3yr^{-1} (million cubic meters per annum) of which :-

- 76.2 Mm^3yr^{-1} is composed of fresh (TDS 500-2500 mg/l) groundwater of which 13.8 Mm^3 is returned to the upper aquifer as irrigation return. One third of this abstraction amounting to 24 Mm^3 yr^{-1} is being utilized for the irrigation of trees, landscape areas, non-productive date palms and limited non-marketed production on amenity farms.

- 3.3 Mm^3yr^{-1} of brackish groundwater (3500-10,000 mg/l) abstracted for agricultural use in SW Qatar and in the Doha area for blending with distilled sea water.

- 44.0 Mm^3yr^{-1} of distilled sea water supplied for exclusive domestic and commercial use of which approximately 14 Mm^3yr^{-1} is lost in distribution and is recharging an aquifer under Doha where it is being polluted by leakage from sewers and overflow from septic tanks. Of the 28 Mm^3yr^{-1} consumed directly approximately 30% or 8.4 Mm^3 is utilized in garden watering of which 20% (1.7 Mm^3) is also being returned to the aquifer.

- 1.6 Mm^3yr^{-1} of treated effluent water is being used for the irrigation of municipal trees and parks.

The full economic cost of water from various sources has been determined to be :

- QR 5.50/m^3 for distilled sea water
- QR 0.85/m^3 for treated sewage effluent delivered to the farm gate from storage within 10 Km.
- QR 0.20/m^3 for groundwater pumped for agricultural use on site.

2.1.11 Mathematical Model and Water Balance

An important component of project investigations was the development of a computer-based mathematical model of the main northern aquifer system, which is the major source of fresh groundwater. The model was based on a grid square nodal configuration covering the northern half of Qatar, an area slightly in excess of the northern aquifer system and in conformity with the hydro-geological interpretation of a two-layered aquifer system. Abstraction was proportioned between the two aquifers in accordance with field data with recharge and irrigation return being assumed to be confined to the upper aquifer. The connection and transfer between the upper and lower aquifer was modelled to conform to other known parameters and observed water levels.

This model has clearly shown the groundwater situation to be in a more precarious situation than hitherto realised. Whereas it had always been assumed that the system behaved as a simple input/output aquifer where in some years recharge might just possibly exceed abstraction, this assumption is no longer tenable because of the geological control at the base of the upper aquifer inhibiting the downward flow of recharge to the higher yielding lower aquifer. Thus, while the upper aquifer is in approximate balance between recharge, (including irrigation return), outflow, transfer to the lower aquifer and limited abstraction the lower aquifer exhibits a progressively increasing deficit and where the freshwater reserve is being irreversably displaced laterally by saline water.

In summary, the mathematical model of the somewhat complex aquifer systems shows that :

- The total annual abstraction from northern Qatar in 1978/79 was 26.7 Mm^3 from the upper (Rus) aquifer and 25.1 Mm^3 from the lower (Umm er Radhuma) aquifer.

- The deficit in both aquifers amounted to 26 Mm^3yr^{-1} in 1978/79.

- At present abstraction rates the advance of the salt water interface is estimated to be at a rate of 1 km/yr^{-1}.

- At present abstraction rates the aquifers will be depleted in 20 -30 years.

2.1.12 Water Resources Development

With large accumulated capital reserves and committed to an energetic development programme, one aim of which is to attain self-reliance in foodstuffs, the Government of Qatar is understandably anxious to undertake a considerable horizontal expansion of agriculture. However, the work of the project has clearly identified the circumscribed natural resource environment of Qatar and the many limitations and constraints militating against such an agricultural policy. The major limitation is the lack of an adequate water resource to sustain such an expansion and another is the adverse climate which imposes a severe constraint to diversified arable crop production on the limited area of arable soils.

To achieve even a modest degree of food self-reliance very large quantities of high-cost water would be required. By 2000 the total domestic/commercial and industrial demand for water will amount to approximately 105 Mm^3yr^{-1}. To meet agricultural demand an additional 250 Mm^3yr^{-1} may be required and the overall total water demand may therefore amount to 355 Mm^3yr^{-1} if such an agricultural policy were to be pursued. Only 11% of this total may be supplied from groundwater resources and future water resources development would have to be based on a very large element of distilled sea water. While the high cost of distilled sea water (QR 5.50/m^3 or QR 25/1000 gallons) may, under present circumstances, be acceptable for agricultural use, it would be imprudent to base the entire future agricultural development of Qatar on a water resource, 90% of which was composed of distilled sea water. Distillation and power plants are vulnerable to accidental failure and an interruption of supply for a period as brief as two weeks could bring about complete crop failure.

Notwithstanding these overwhelming arguments against major expansion of agriculture based on a very large element of distilled sea water, the project has presented a number of specific proposals for agricultural development based on the optimised conjunctive use of groundwater, sewage effluent water and distilled sea water and/or saline groundwater. However, these proposals raise a number of complex issues and more importantly do not analyse the complicated technical, economic and social inter-relationships of each part of the problem to every other part as well as the inter-relationships to each other, among objectives and the means by which they may be achieved. The optimal apportionment of the different sources of water and their relative inter-relationship to each other for different uses was therefore subjected to systems analysis. This analysis brought together all factors affecting water resources and agriculture in determining how groundwater, distilled water and effluent water could be most efficiently and economically combined to meet estimated agricultural, industrial and domestic needs by the year 2000. Eight alternate plans were examined from which four possible basic policies were identified, the choice essentially depending upon the level of agriculture desired. These four policy options are as follows :

I Concentrate on the production of economic crops of vegetables based on the safe-yield of groundwater only. Under this plan annual farm and water costs would be QR 45 million and food imports would be QR 145 million.

II Expand agriculture to make full use of the safe yield of the groundwater and all available treated effluent water. Under this plan the maximum possible amount of milk, beef and vegetables with some additional mutton could be produced at an annual cost of QR 75 million and thus reducing annual food imports to QR 115 million.

-I By supplementing groundwater (19 Mm^3) and treated effluent water (11 Mm^3) with almost an equivalent quantity of distilled water (35 Mm^3) would enable the production of all crops except cereals and mutton to the maximum practical limit. In this case the annual costs would be QR 280 million and food imports would be reduced to QR 90 million and the farmed area would be 4,800 hectares.

Expand agriculture to its practical maximum extent in terms of available land (17,600 ha.) to include cereals and mutton. In this case the annual cost would rise dramatically to an annual cost of QR 1940 million and food imports would be negligible.

The proposals presented assume that the Government of Qatar will first select their required level of agricultural activity and that the development of water resources will be organised to satisfy the overall water demands of the country. The proposed Agricultural Development Plan is a practical interpretation of Policy III. This Policy involves raising the levels of agricultural production of all suitable crops except cereals and mutton to the level at which the greatest practicable amount of imports had been replaced. The reasons for this choice are discussed in detail in Chapter XIV.

Under this Plan, the demand for water for productive agriculture rises from 53 MCM in 1980 to about 69 MCM in the year 2000, to which should be added the demands from other sectors. However, not all of the demands need to be considered directly in preparing an overall plan. Industrial and other consumers with their own distillation plants may be excluded and the specific requirements in Doha for landscaping (0.7 MCM in 1980) may in future be met by the development of the freshwater dome building up under the city. The remaining demands are for productive agriculture, amenity farms, central potable supplies and isolated domestic supplies not drawn from agricultural wells. These isolated supplies amount to about 0.8 MCM, and may be expected to continue at a similar level. The demands from each of the three remaining sectors rise from 124 MCM in 1980 to 196 MCM in the year 2000.

The most practical large source of distilled water in Qatar would be multi-stage flash distillation associated with waste heat from thermal power stations or industrial processes. The installations at Ras Abu Fontas and Ras Abu Aboud could produce about 64 MCM at present at a load factor of 75 per cent. This capacity will rise to 88 MCM when the installation of four new units and ancilliaries is completed in the next 2-3 years. No further extension to either plant is planned and future desalination facilities are proposed at Ras Laffan. The results obtained from this Study confirm that there are no cheaper or more reliable sources of water, and that any deficit in Qatar's supplies should be made good by increased capacity at Ras Laffan.

Under the suggested Water Resources Development Plan, the dependence of productive agriculture upon groundwater would be reduced in order to curtail the over-abstraction in the north to restore equilibrium with recharge. This would involve :

- continuing abstraction at their present level until 1985; then
- reducing the level of net abstraction progressively to 27 MCM/year in 1990; and
- continuing thereafter at the lower abstraction rate.

Under this operating rule, the overall net abstraction rate for the next 30 years would be equivalent to the safe yield of 33 MCM.

The quantity of distilled sea water required would however, be considerably reduced if treated sewage water could either be made available in the north east of Qatar or if the quality constraints could be relaxed. Neither of these changes has been incorporated into the Water Resources Development Plan and so Ras Laffan would be called upon to produce about 29 MCM in 1990 rising to 45 MCM in the year 2000. Although in theory there would be spare capacity at Ras Abu Aboud and Ras Abu Fontas in 1990, the construction of a special di...

agricultural demands have been assumed to be met from Ras Laffan.

The total annual water demand figures derived in the foregoing show a considerable variation in demand within the year. The importance of these variations depends upon the source of supply concerned.

Assuming that the groundwater reservoir will be properly monitored and good practice encouraged, groundwater abstractions could be regulated to reduce the peak demands on other sources, particularly desalination. Under the suggested Plan, distilled sea water for agriculture is proposed for irrigation in northern Qatar, close to the Ras Laffan site. After subtracting the groundwater supply in a suitable temporal pattern, the agricultural demand for distilled water was found to range from 1.7 to 2.7 MCM/month in 1990, and from 2.1 to 3.3 MCM/month in 2000. By combining agricultural demand with the potable demand the total pattern of demand for distilled water it is concluded that the installed distillation capacity at Ras Laffan will need to rise to 33 Mm^3yr^{-1} by 2000, representing 4 units and 7 units respectively of the size currently installed at Ras Abu Fontas and proposed for Ras Laffan. In effect, present existing distillation capacity would need to be doubled by 2000 to meet all agricultural and domestic requirements.

2.2 RECOMMENDATIONS

2.2.1 During the course of the project a number of major recommendations were made to the Government of Qatar which in due course were either accepted in their entirely or incorporated within wider internal organizational matters prior to project termination. The first of these was a recommendation to continue the work of the project, which had been organized as a separate entity successfully integrating staff and equipment provided by both the Ministry of Industry and Agriculture and the Ministry of Electricity and Water. This resulted in a decision by the Council-of-Minister's to establish a new department - the Department of Agricultural and Water Research - within the Ministry of Industry and Agriculture to continue the work of the project immediately upon project termination on 1st May 1981. Secondly, as a result of a number of audiences with His Highness The Emir of Qatar, Sheikh Khalifa Bin Hamad Al-Thani, arising out of earlier memoranda on the continued and worsening groundwater deficit, an Amiri decree prohibiting the drilling of new wells throughout the country, except in cases of exploration and investigation, was promulgated.

2.2.2 Qatar is one of the countries making up a region which has a large food deficit. The present food gap is alarming; the region is the highest per capita food importer in the world which constitutes a grave problem with far-reaching implications. The long-term demand for food poses an unprecedented challenge to food production in the region and unless production efforts are intensified, dependence of imported food will probably reach an unsupportable limit and bring-about serious socio-economic problems. The Government of Qatar is keenly aware of this problem and has decreed that all future deliberations in future agricultural development should have as their objective the attainment of self-sufficiency in basic foodstuffs.

In the final chapter of this report a summary of the detailed systems analysis study undertaken by consultants to the project to provide a number of policy options has been given and a suggested development plan put forward. This systems analysis study has shown very clearly the limited choice of options open to the Government of Qatar in developing agriculture and complete self-sufficiency is not a practical policy. While four possible policy options are presented for consideration, the choice is in reality limited to one of two of these if the overall objective of food self-reliance is to be pursued. Whilst it is for the Government of Qatar to decide which policy they wish to pursue, it is strongly recommended that urgent consideration be given to the suggested plan outlined in the foregoing section and based on policy option III. This provides for raising the level of production of all suitable crops except cereals and sheap-rearing to that which the greatest practicable amount of imports are replaced. By including both cereals and sheap-rearing the water requirement would be increased by a factor of 3.5 and the annual cost five-fold. Even if the additional high cost of water is ignored, these two items could still only be produced at several times their import cost.

But apart from these overwhelming economic arguments against including these in many plan is the undesirable necessity of basing almost the whole agricultural sector on a very high proportion of distilled sea water. Under the recommended plan the proportion of distilled sea water to that from other sources is about equal, but if cereals and sheep-rearing are included, this proportion would rise to 87% of the total. This would render agriculture vulnerable to complete failure if for any reason the installation were to be interrupted for even a short period.

2.3 As a corollary to the above recommendation would be the need to reduce abstraction of groundwater from the northern aquifer in accordance with the phased programme presented in foregoing section.

2.2.4 In drawing-up a development plan based on the systems analysis study it has been realised that the practical implementation of any one of the options presented would be difficult given the present agricultural situation in Qatar. The greatest problem does not lie with devising a suitable plan and strategy but in the creation of the incentives necessary to motivate owners, managers, tenants and farm workers. In particular, it is recommended that steps be taken by Government to educate the farming community to :

(a) develop an interest in serious, efficient agriculture among Qatari landowners

(b) create a general awareness of the need for water and land conservation

(c) to persuade landowners and farmers to adopt economic farm planning in accordance with market forces

(d) to persuade owners to adopt efficient irrigation methods and inculcate an awareness of the need to reduce the abstraction of groundwater.

2.2.5 A feasibility study of the Wadi el Araig area be undertaken by consultants to determine the economic and technical feasibility of developing large areas of dune sand in that area based on poor quality groundwater. Terms of reference have been prepared by the Project.

2.2.6 A design study of the El-Ashara project based on treated sewage effluent water area should be carried out by consultants within the immediate future. Terms of reference have been prepared by the project.

2.2.7 An investigation of the magnitude of leakage of desalinised water and the associated groundwater situation within the Doha city area be undertaken. This study should propose a practical system of reducing, recovering and treating leakage for beneficial use.

2.2.8 A countrywide investigation leading to the design and implementation of constructing simple water retaining and induced recharge structures at suitable locations be undertaken based on work already carried out by the Project.

2.2.9 A renewed exploratory drilling programme be initiated by the Department of Agricultural and Water Research. This programme should be designed to explore groundwater conditions in certain special areas and thereafter maintained as monitoring wells to check on changes in quality. This is particularly important as deterioration in quality tends to occur over a relatively short-time from vertical upconing of deeper saline water.

2.2.10 In the short and medium terms, as a parallel activity to longer-term planning and implementation, the Ministry of Industry and Agriculture should be strengthened to undertake a comprehensive agricultural extension programme not only to raise general cultivation practices and increase production but to improve irrigation efficiency and reduce the high rate of water extraction through remedial works, controls and adequate provision of financial assistance and subsidies. In particular; action should be taken to :-

- Construct artificial recharge works in combination with flood protection works wherever possible.

- Construct drainage systems within depressed farm areas to remove damaging excess rain-water.

- Improve the efficiency of pumps and engines through subsidized replacement programmes.

- Reduce water transmission losses through the provision of gated pipe for water distribution

- Introduce more effective irrigation methods for border strip, proper scheduling, reducing frequency, soil preparation and leaching.

III

GEOLOGY

3.1 INTRODUCTION

3.1.1 Topography

The surface of the Qatar peninsula is of low to moderate relief, with the highest elevation of 103 m above sea level being attained in southern Qatar where mesa type hills and large barchan sand dunes serve to break the monotony of an otherwise flat eroded landscape.

The most pronounced topographical features are created by the large number of shallow depressions which are the surface expression of subsurface collapse structures of the type defined in karst hydrogeological studies as poljes. The solution and removal of subsurface anhydrite and calcium carbonate, and the dolomitisation of superficial limestones has been extensive, resulting in the formation of some 850 of these depressions, approximately circular in shape and with diameters ranging from a few hundred metres upto about three kilometres. Generally they form small internal surface catchments which are the focus for storm run-off water. In northern Qatar where most of the soluble material has been removed and the process is less active, the depressions have been infilled to depths of up to 1.5 m with colluvium which masks their original form and gives rise to a gently rolling terrain with often only low ridges separating adjacent depressions. In southern Qatar where subsurface anhydrite remains and the solution activities continue, the depressions are often more crater-like in appearance, with the floor sometimes as much 20 m below the adjacent ground level.

The central part of the peninsula is formed by a plateau known locally as barr Qatar[1/] and the whole is covered with a mantle of limestone debris known simply as hasa[2/] except in the depressions where colluvial soils have accumulated. Such depressions are sometimes referred to simply as rōda (pl. rōdat or riyād)[3/] but several names are used, the distinction sometimes being very fine. The place names associated with many depressions are often prefixed by Umm or Abu ("mother or father of", i.e. possessor of some natural feature, animal or tribal incident). The depressions are classified by vegetation, soil and size and two main types may be distinguished. Depressions referred to as rōda are where semi-permanent grazing, in the form of low-lying grass known as naǐm (Dactyloctenium aegyptium), occurs. The other type, known as jirī (pl. jiryān), is characterised by shrub and tree vegetation; a flat floor or manga in the lowest part where storm water accumulates, surrounded by bare hard pan (mistah), this part also known as suna[4/]. Leading to these depressions are water courses simply known as wadi although short stream courses in which no vegetation is found are referred to as shi'b (pl. she'ub). The slight rises between depressions are generally referred to as hazm but this term is generic and there are several types. A high rocky hill is known as lihzila[5/], whereas a low rocky

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1/ Barr, which means in literary Arabic, 'land continent' in the Gulf usually means 'desert' although in Qatar it seems to have the meaning 'stone desert'.

2/ See H.St. J.B. Philby, ('Heart of Arabia', 1922) on the meaning of hasā.

3/ This is a widely used term and is also Cl. Arabic, but the definition given above is in terms of local concepts. H.R.P. Dickson, 'Kuwait and her neighbours' (1956) p. 602;'wide open vale or depression containing good grazing, owing to rainwater having formed a lake during winter and kept the ground moist'. Cf. A Musil, 'Manners and Customs of the Rwala Bedouins' (1926) p. 682, 'lower ground in a level desert, into which silt is deposited by rainwater, producing a growth of perennials'.

4/ Hubber, C. 'Journal d'un voyage en Arabie', (1891) defines suna' differently (p. 183), namely as underground cisterns hollowed out of rock, as does Musil (op cit, p. 683) under sen' : 'an artificial hollow in a rocky surface where rainwater remains'. The words jirī and manga' are not encountered elsewhere in the Gulf as topographical terms although the latter has the related meaning of 'swamp' in Cl. Arabic.

5/ Lihzila is not classical nor apparently used outside Qatar.

mound is called hdiba[6]. The whole of the Dukhan range is known as mashabiyya but the separate hills which form it are so large, by Qatar standards, that they are simply known as jabal. Wind-eroded hills which are prominent on the eastern flanks of the range are sometimes known as gehab[7], and the hills which form very marked scarp with frequent outliers of soft white chalky limestone capped by a secondary carbonate duri-crust, are known as briga (pl. abrag)[8] because of the brightness of the rock which makes them stand out clearly.

The coastline of Qatar is gently emergent and presents an uneven outline with numerous inlets, islands, reefs, capes and bays and extensive areas of sabkha (pl. sebākh)[9] or saline coastal playas. The prevailing wind in Qatar is from the northwest (shemāl) and aeolian sand deposits in the form of migrating isolated barchan sand dunes (ti's, pl. te'us or khēt pl. keyūt or khuweyit) have coalesced to form an extensive dunefield (nigyan) in the Khawr al 'Udayd region of south eastern Qatar. In addition many of the depressions of southern Qatar have been infilled with aeolian sand deposits upon which vegetation has become firmly established. In contrast, the depressions of northern Qatar generally do not contain aeolian sand deposits and vegetation.

In general the peneplaned and eroded nature of the peninsula coupled with a prolonged arid climate provides very few positive topographical features except in the south-west. As a result the topography does not provide a significant insight into the geology and most of the geological interpretation has had to be based on sub-surface data.

3.1.2 General Geological Setting

Qatar forms an exposed part of the Arabian Shelf between the stable Arabian Shield of western Saudi Arabia and the Mobile Belt of south-western Iran. Schlumberger (1975), in a wide ranging lithological and structural overview, placed Qatar within the Interior Plantform of the Shelf between the basins of the Northern Arabian Gulf and the Rub al Khali (Fig. 3.1). Within these basins, sedimentation was continuous, stratigraphic lacune are few, and the deposits are relatively thicker. Over the Interior Platform, thinner, lithologically more variable deposits accumulated and hiata are frequent. A generalised geological map of the Arabian Peninsula is given as Fig. 3.2.

Precambrian rocks form the Arabian Shield of western Saudi Arabia and are overlain to the east by a succession of sediments ranging from the Cambrian to the Quaternary. While erosion of the permanent land surface of the Arabian Shield provided the material, the tilting and gradual but continuous subsidence of the region to the north and east formed the geosynclinal trough for deposition. The accumulation of large volumes of sediment beneath this shallow Tethys Sea, acted upon by the forces of crustal drift, lead to the instability and orogenic activities which created the mountain chains of the Zagros and Oman. A remnant of the Tethys Sea forms the present-day Arabian Gulf where modern sediments are forming.

Thus the environment for the accumulation of a great thickness of sedimentary rocks was basically shallow-water, marine with frequent intercalations of very shallow, brackish water, evaporitic periods as well as times of exposed, continental conditions when erosion of previously deposited material took place.

In the area of Qatar, sandstones, silts and shales marked periods of greater erosional activity and transport both from the Shield as well as younger siliciclastic rocks, while limestones denote quieter, clearer-water conditions in which biogenic and chemogenic

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6/ Hdiba is used in southern Qatar to denote any sand dune.

7/ The root means 'grey dust-coloured'.

8/ The word, or alternative forms from the same root, is commonly used in Arabia. Cf. Dickson op.cit., p. 588, and Musil, op.cit., p. 676, refer to abrag. In Qatar the brilliant white rock has given the name Abarug to the stratigraphic division at the top of the Eocene.

9/ Sabkha is Cl. Arabic; locally Sbakha, sīn and sād.

Structural Provinces; Arabian Peninsula

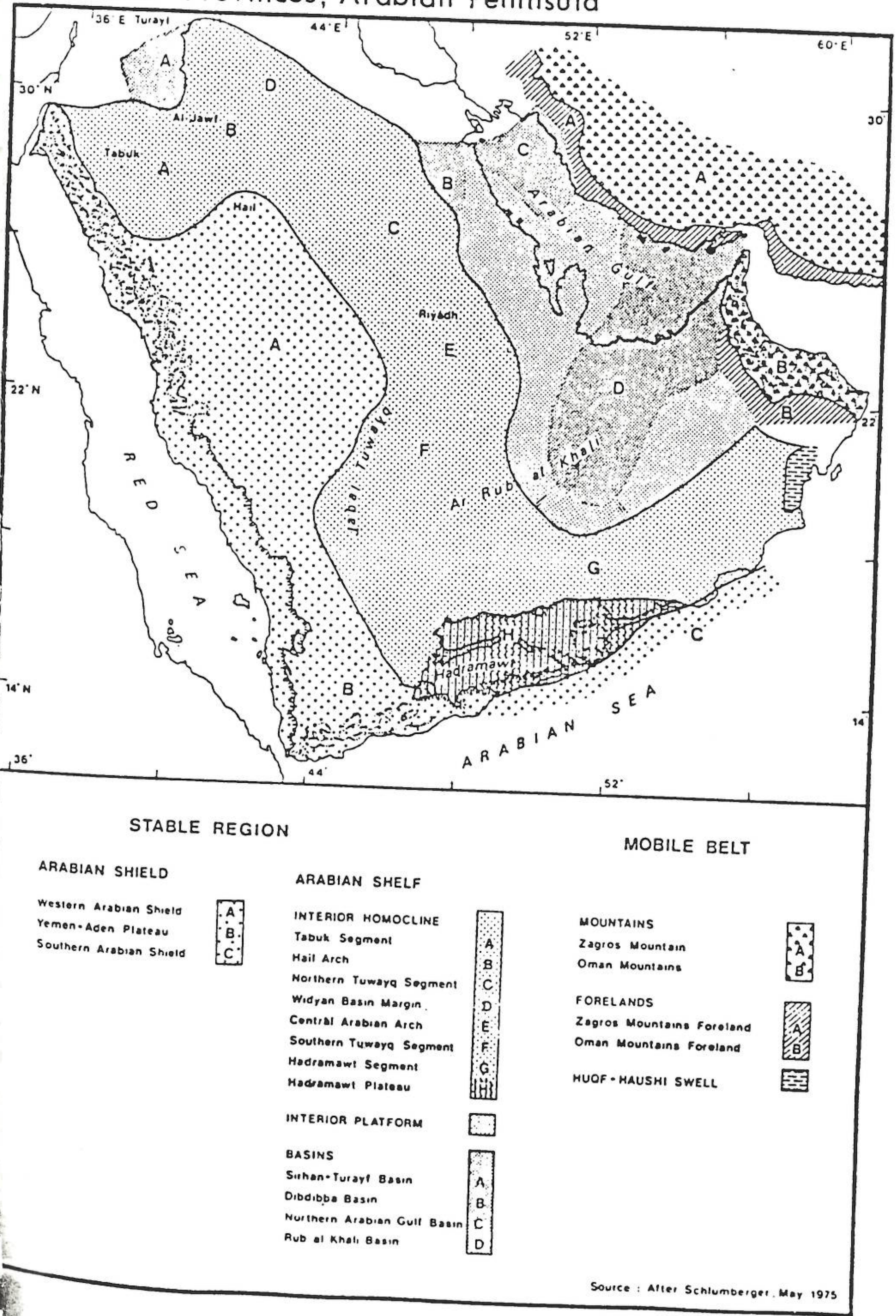
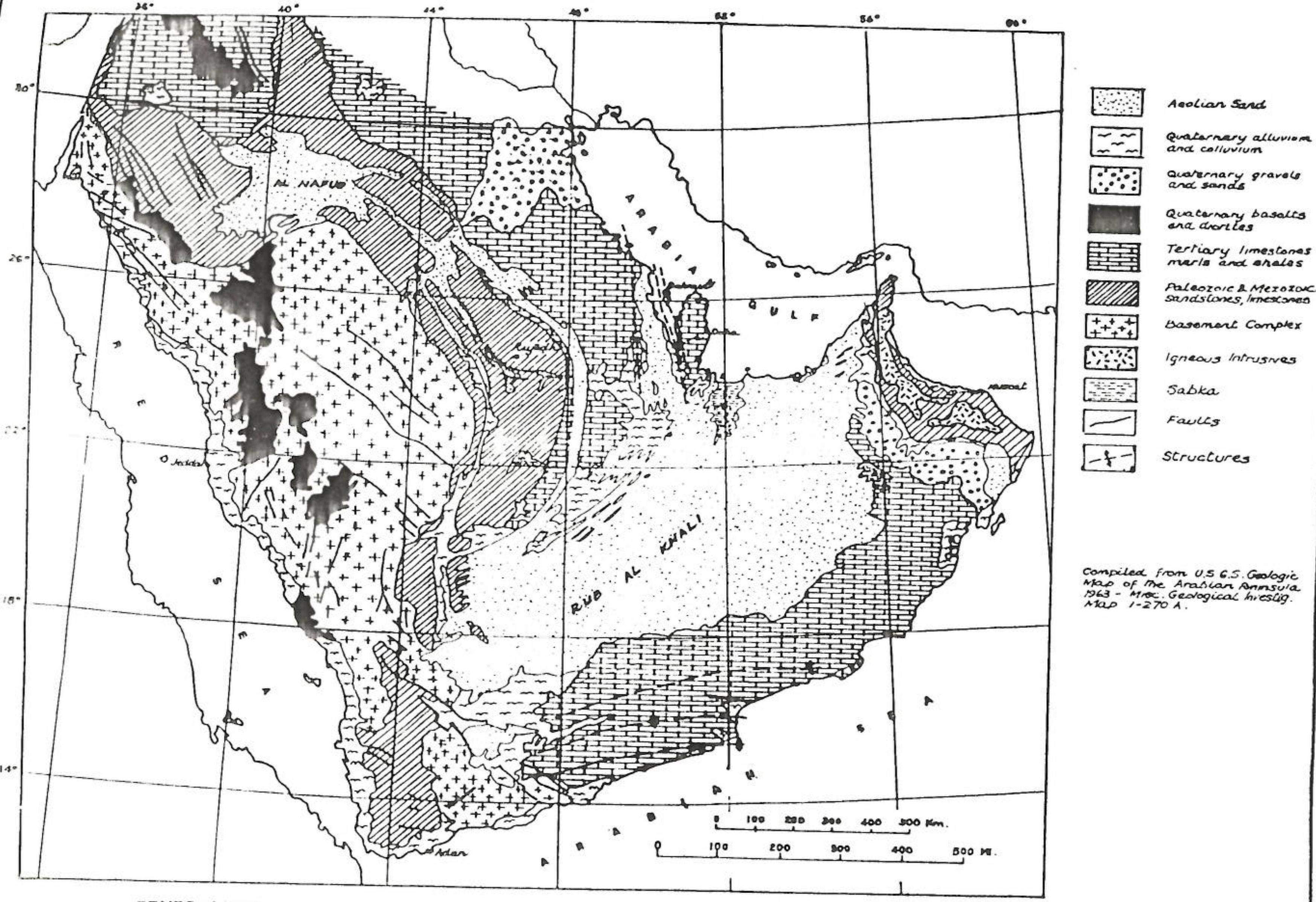


Fig. 3.1



GENERALISED GEOLOGICAL MAP OF THE ARABIAN PENINSULA

JGP

mulation took place.

Anhydrite and halite are also present indicating isolated evaporative conditions in ıl'low lagoons separated from the main sea area.

In its position adjacent to the Tethys geosyncline, Qatar has been subject to minor olding which has had a significant influence upon sedimentation. The present peninsula efined by a northerly trending gentle structural high (pericline) and a steeper flanking anticline which have probably been active since the early Tertiary and may be partly alokinetic in origin. The long-term structural movements have controlled deposition such sedimentation has been relatively thicker away from the positive axes, particularly si..e the Palaeocene.

3 Previous Studies

The first most comprehensive geological study pertinent to the hydrogeology of Qatar that carried out by Cavalier (1970) for the Department of Petroleum Affairs. Prior his a large volume of data for the oil industry, relating to the deeper strata had been compiled, little of which contains information of hydrogeological significance for r resources evaluation. Cavalier carried out field mapping and produced 1:100,000 e geological maps accompanied by an explanation entitled "Geological Description of the Qatar Peninsular" integrating previous mapping carried out by the Qatar Petroleum mpany and Le Grande Adsco (1959). This work has provided the base for much geological subsequent hydrogeological interpretation of the upper strata of peninsula and reliable correlations between the formations of Qatar, adjacent areas in the Arabian Gulf and Saudi abia have been facilitated.

Following Cavalier's study which was never completed, the only fundamental geological nvestigation, other than the project work, has been a study for exploitable mineral sits carried out by Seltrust Engineering Ltd. U.K. for the Qatar Government. As part he work, a revised geological map of Qatar was produced related to an updated topograhic base. The accompanying "Explanatory Booklet" follows the system laid down by lier but with the major addition of the outcrop of the Lower Dammam Formation and sions to the outcrop areas of Rus Formation. This map is reproduced as Enclosure 1. ome of the geophysical survey data, collected during the minerals survey, have also been available and the results of a regional airborneresistivity survey by Geoterex Ltd. 9) have been incorporated into this report.

4 Purpose of Present Geological Studies

The geology described in this chapter has been compiled with the objective of taining an accurate framework for hydrogeological interpretation and groundwater resources stigation. Two main aspects of the geology have been examined for their influence on ydrogeology. These are :

) the lithostratigraphic distributions that would influence groundwater movement and storage, and

) the sequence of geological events, mainly post-Tertiary, which have affected the evolution of the aquifers.

The first of these two aspects has proved the most important, but difficult to idate due to the complexities discussed below.

In the geological complication, pre-project data have been carefully reviewed and porated within project lighological interpretations together with surface and borele geophysical information. With respect to groundwater resources development, rocks age greater than the Palaeocene contain highly saline water and the main emphasis has therefore been concentrated on the Palaeocene and younger strata. As mentioned above (see 3.1.1) the subdued topography and the fact that the Simsima Dolomite and Limestone Member of the Upper Dammam Formation forms about 90% of the outcrop in Qatar has required that the interpretation be based essentially on subsurface data.

3.1.5 Drilling Information

Fundamental to any hydrogeological and water resources investigation is the need for sub-surface geological, geochemical and hydrogeological data which can only be provided by the drilling of exploratory boreholes. To this end successive FAO projects since 1972 have undertaken the drilling of 37 boreholes with a combined depth of some 5300 m in three separate programmes. The first and second programmes, drilled by local contractors, using Dando percussion rigs provided only limited data of a reconnaissance type and it was not until the Project obtained a Failing 1500 rotary drilling rig in November 1977, that significant results were forthcoming. In the light of data obtained during the 1977-80 drilling programme a re-appraisal of some of the information obtained during the second (1975) programme (El-Hadi, 1976; Technical Note No. 35) was made.

As part of the subsurface interpretation and in order to prepare and carry out a sensible Project drilling programme a review of the pre-project drilling data was made. The processed geological data are included in Appendix 3.1 and the borehole locations are shown on the maps which form the basis of Enclosure 3, 4 and 5.

Some 600 boreholes have been drilled into the Dukhan structure; 150 deep wells for the exploration and expoitation of oil and gas and 450 to shallow depth to provide the large quantities of water required to drill the deeper wells and for water injection. The early oil exploratory boreholes were interpretated to provide detailed stratigraphy of the Tertiary formations but during subsequent drilling only the E_1 marker horizon (the Dukhan Alveolina Limestone) has been recorded within the strate sequence of importance in hydrogeological studies. This limited stratigraphic information has been of value however in the interpretation of structure though the data are not recorded in Appendix 3.1.

More than 3000 boreholes have been drilled in Qatar in the search for and development of groundwater for agriculture alone. In the absence of legislation requiring the submission of requests for drilling permission, the registration of drilling results and completion reports and the regular licencing of abstraction, there are no geological data available on those wells other than can be obtained by post-construction surveys. A similar situation applies to about 1000 boreholes which have been drilled in close-set patterns to form the wellfields supplying potable groundwater to the main centres of population.

Geological details of Project exploratory drilling is given in Appendix 3.2. The locations of these boreholes are shown separately on Fig. 3.3 as well as being included on the base map forming Enclosure 3, 4 and 5. Most boreholes were drilled to penetrate at least the upper 10 metres of the Umm er Radhuma Formation, though P21 and P22a, in the centre of northern Qatar, and P29b on the west coast were continued to about 100 m into the Formation. P33, a 192 m exploratory hole in the southwest, reached only 5 m into the Formation because of the very thick Rus in that area.

Project Exploratory Drilling

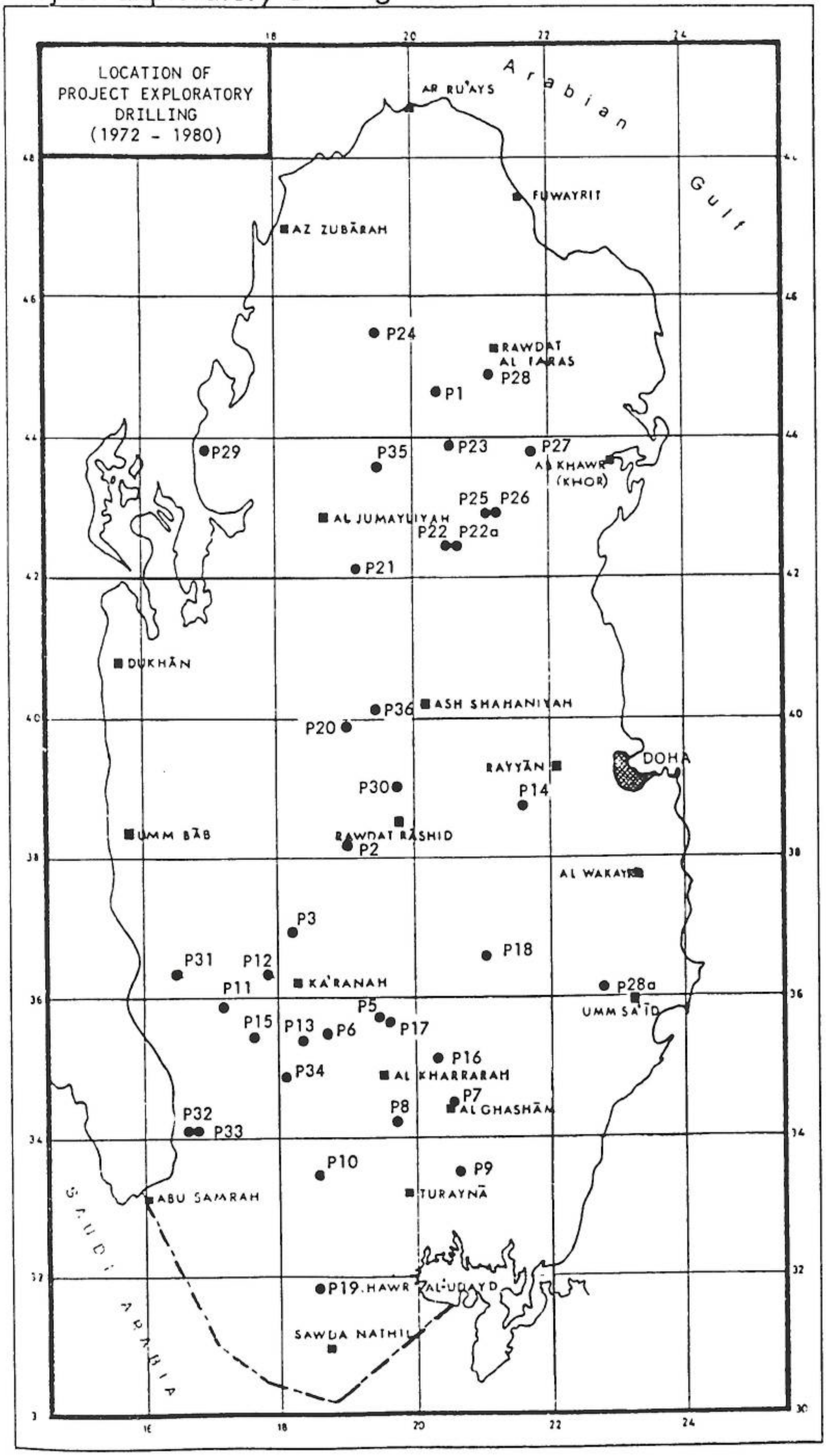


Fig 3.3

3.2 GEOLOGICAL SUCCESSION

3.2.1 Introduction

The generalised stratigraphy for Saudi Arabia and the western Arabian Gulf area was compiled by Powers et al (1963) and is shown in Table 3.1. Much is known of the Mesozoic and Cenozoic succession beneath Qatar though only the Tertiary sediments and to some extent the Quaternary deposits are pertinent to the present study.

The stratigraphic nomenclature adopted for the project study is given in Table 3.2 where it is also correlated with Bahrain and Saudi Arabia to establish the regional setting. To provide continuity the formational nomenclature used for the geological sequence in Qatar by various previous geological surveys is shown in Table 3.3. Despite some differences in formational names between countries the Tertiary geology is reasonably well known and the correlations are reliable. The Quaternary geology is less well understood. Details of the formational subdivisions, thicknesses, lithologies and their hydrogeological significance in Qatar from Table 3.4. The surface geology of Qatar is presented as Enclosure 1 with geological cross sections forming Enclosure 2.

Eocene, Miocene and Pliocene deposits outcrop over the peninsula and are overlain locally by Quaternary and Recent deposits. The oldest strata exposed are those of the Rus Formation which are of Lower Eocene age. The Palaeocene, Umm er Radhuma Formation, which directly underlies the Rus Formation throughout Qatar, is not exposed at the surface.

3.2.2 Mesozoic Succession

Mesozoic rocks are not exposed in Qatar but their presence at depth has been confirmed during exploratory oil drilling by stratigraphical correlation with geological units in Saudi Arabia. Upper Jurassic calcareous rocks of the Arab Formation comprise the oil reservoir rocks in the Dukhan anticline, where the top of the formation lies at a depth of about 1400 m below ground surface. The Cretaceous sequence consists of up to 800 m of calcarenitic limestones, dolomites, sandstones and shales. Details of the Mesozoic stratigraphy for adjacent parts of Saudi Arabia are shown on Table 3.1 with discussions included in Powers et al (1966), Schlumberger (1975) and BRGM (1976).

The uppermost Cretaceous unit is the Aruma Formation which consists of hard, massive, crystalline, marine limestones with some shale and marl. The contact between the Aruma and overlying Umm er Radhuma Formation is conformable and, in terms of lithology, can usually be recognised by the presence of dark-coloured shales and marls which stratigraphically occur in the basal section of the Umm er Radhuma. In Bahrain the top of the Aruma is placed where dolomitic and marly limestones give way to 10 m of shale with some marly limestone.

In Qatar, the Aruma Formation, which is believed to range in thickness from 100 to 180 m, has been drilled extensively in the oil wells of the Dukhan area. Elsewhere is the peninsula it has also been penetrated in a few exploratory oil wells for which records are not generally available. Records from Ruwais No. 1A (Almojil 1963, see Appendices 3.1 II and 3.3) in northern Qatar indicate the following lithologies for 63 m of partial penetration of the Aruma Formation.

Aruma Formation Lithological Description

Borehole Ruwais 1A (Almojil)

Base of Umm er Radhuma

	Thickness (m)
Dolomite, grey to buff, granular, hard and dense to friable	20
Dolomite (as above)/Limestone, soft, white	3
Dolomite, crystalline, granular	5

Generalized Stratigraphy

Age				Formation	Generalized lithologic description	Thickness (Type or reference section)	Major stratigraphic divisions
CENOZOIC	QUATERNARY AND TERTIARY			Surficial deposits	Gravel, sand, and silt		
	TERTIARY	Miocene and Pliocene		Kharj	Limestone, lacustrine limestone, gypsum, and gravel	28 m	Miocene and Pliocene Clastic Rocks
				Hofuf	Sandy marl and sandy limestone; subordinate calcareous sandstone. Local gravel beds in lower part	95 m	
				Dam	Marl and shale; subordinate sandstone, chalky limestone, and coquina	91 m	
				Hadrukh	Calcareous, silty sandstone, sandy limestone; local chert	84 m	
		Eocene	Lutetian	Dammam	Limestone, dolomite, marl, and shale	33 m	Upper Cretaceous to Eocene Carbonate Rocks
			Ypresian	Rūs	Marl, chalky limestone, and gypsum; common chert and geodal quartz in lower part. Dominantly anhydrite in subsurface	56 m	
		Paleocene	Thanetian Montian(?)	Umm er Radhuma	Limestone, dolomitic limestone, and dolomite	243 m	
				Possible disconformity			
MESOZOIC	CRETACEOUS		Maestrichtian Campanian	Aruma	Limestone; subordinate dolomite and shale. Lower part grades to sandstone in northwestern and southern areas of outcrop	142 m	
			Turonian(?) Cenomanian	Wasia (Sakaka Sandstone of northwest Arabia)	Sandstone; subordinate shale, rare dolomite lenses	42 m	Middle Cretaceous Clastic Rocks
			Aptian Barremian	Biyadh	Sandstone; subordinate shale	425 m	Late Lower Cretaceous Clastic Rocks
			Hauterivian	Buwaib	Biogenic calcarenite and calcarenitic limestone interbedded with fine sandstone in upper part	18 m	
			Valanginian	Yamama	Biogenic-pellet calcarenite; subordinate aphanitic limestone and biogenic calcarenitic limestone	46 m	Upper Jurassic and early Lower Cretaceous Carbonate Rocks
			Berriasian	Sulaiy	Chalky aphanitic limestone; rare biogenic calcarenite and calcarenite limestone	170 m	
	JURASSIC		Tithonian	Hith	Anhydrite	90 m	
				Arab	Calcarenite, calcarenitic and aphanitic limestone, dolomite and some anhydrite. Solution-collapse carbonate breccia on outcrop due to loss of interbedded anhydrite	124 m	
			Kimmeridgian	Jubaila	Aphanitic limestone and dolomite; subordinate calcarenite and calcarenitic limestone. Lower part sandstone between 20° N. and 22° N.	±118 m	
				Hanifa	Aphanitic limestone, calcarenitic limestone, and calcarenite	113 m	
			Oxfordian Callovian	Tuwaiq Mountain	Aphanitic limestone; subordinate calcarenitic limestone and calcarenite. Abundant corals and stromatoporoids in upper part	203 m	
			Callovian(?) Bathonian Bajocian	Dhruma	Aphanitic limestone and shale; subordinate calcarenite. Dominantly sandstone south of 22° N. and north of 26° N.	375 m	Lower and Middle Jurassic Clastic and Carbonate Rocks
			Toarcian	Marrat	Shale and aphanitic limestone; subordinate sandstone	103 m	
	TRIASSIC		Upper	Minjur	Sandstone; some shale	315 m	Permian and Triassic Clastic Rocks
			Middle	Jilh	Sandstone, aphanitic limestone, and shale; subordinate gypsum	±326 m	
			Lower	Sudair	Red and green shale	116 m	
PALEOZOIC	PERMIAN		Upper	Khuff	Limestone and shale; dominantly sandstone south of 21°N.	171 m	
			Lower	Wajid	Sandstone, gravel, and basement erratics (Recognized only in southwestern Saudi Arabia and northern Yemen)	950 m calculated	
	— ? —		undated				
				Precambrian basement complex			
	DEVONIAN		Lower	Jauf	Limestone, shale, and sandstone	299 m	Lower Paleozoic Clastic Rocks
	ORDOVICIAN AND SILURIAN			Tabuk	Sandstone and shale	1,072 m	
	CAMBRIAN			Saq { Umm Sahm, Ram, Quweira, Siq }	Sandstone	+600 m	

Precambrian basement complex

Compiled by R. W. Powers and L. F. Ramirez, June 3, 1963

Table 3.1

Regional Stratigraphic Nomenclature

PERIOD/SERIES	Saudi Arabia (Powers et al 1966)			Bahrain (Willis, 1967)		Bahrain (GDC 1980)	Bahrain (Brunsden et al 1979)			Qatar (Cavalier 1970)		Qatar (Seltrust 1980)
Neogene												
Recent - Pliestocene	Superficial Deposits	–	–	Superficial Deposits	–	–	Superficial Deposits		–	Superficial Deposits	–	–
				Ras al Aqr Formation			–	Ras 'al 'Aqr Formation				
Paleogene												
Miocene - Pliocene	Hofuf Formation	–	Conglomerate Sandstone Limestone Conglomerate	–	–	–	–	–	–	Hofuf Formation	–	–
Miocene	Dam Formation	–	–	'Jabal Cap' Formation	–	—	–	Jabal Cap Formation	–	Dam Formation	Upper Lower	– –
? Lower Miocene	Hadrukh Formation	–	–	'Neogene' Formation	–	–	–	–	–	–	–	–
Eocene	Dammam Formation	Alat	Limestone	Dammam Formation	Alat	Limestone	Dammam Group	Jabal Hisai Carbonate Formation	–	Upper Dammam Formation	Abarug Member	Dol. 1st Marl
		Alat	Marl			Orange Marl		West Rifā' Flint Formation	–			
		Khobar	Limestone Marl		Khobar	Dolomite Marl		Al Buhayr Carbonate Formation	–		Simsima Member	Dolomite Limestone
					Alveolina Limestone	–		Foraminiferal Carbonate Formation		Lower Dammam Formation	Dukhan Alveo-lina Lime-stone	–
		Alveo-lina	Limestone		Sharks Tooth Group	–		Dil 'Rafah Carbonate Formation	–		Midra Shales	–
											Fhaihil Velates Limestone	-
	Rus Formation	Saila Shale	-	Rus Formation	-	-	Rus Group	Hafira Carbonate Formation	-	Rus Formation	-	-
		Midra Shale	-									
		-	Limestone					'Awālī Carbonate Formation	-			
		-	Marl and Limestone									
		-	Limestone									

Table 2.2

PERIOD/SERIES	Saudi Arabia (Powers et al 1966)			Bahrain (Willis, 1967)		Bahrain (GDC 1980)	Bahrain (Brunsden et al 1979)			Qatar (Cavalier 1970)		Qatar (Seltrust 1980)
Eocene	Rus Formation	Saila Shale	-	Rus Formation	-	-	Rus Group	Hafira Carbonate Formation	-	Rus Formation	-	-
		Midra Shale	-					'Awālī Carbonate Formation	-			
		-	Limestone									
		-	Marl & Limestone									
		-	Limestone									
Palaeocene	Umm er Radhuma Formation	-	Dolomite	Umm er Radhuma Formation	-	-	Umm ar Radhuma Group	-	-	Umm er Rhadhuma Formation	-	-
Upper Cretaceous	Aruma Formation	-	Shale and Dol. Dolomite Limestone and Shale Calcarenite	Aruma Formation	-	Shale ?	Aruma Formation	-	-	Aruma Formation	-	-

Table 3.2 cont'd.

Qatar Stratigraphic Nomenclature: Correlation of Terms

ERA	PERIOD	EPOCH		Le Grand Adsco (1959)			Parsons (1962)		Amojil (1963)		Cavalier (1970)			
					Formation	Thick. m	Formation	Thick. m	Formation	Thick. m	Formation	Sub form	Member	Thick. m
CAINOZOIC	NEOGENE	HOLOCENE			Blown sand	-	Eolian Sand	0- 3	-	-	Superficial deposits	-	-	-
					Sabkha	0-15	Sabkha	0-15						
					Depression muds and silt	0- 3	Silts & Sands	0- 3						
		PLEISTOCENE			Miliolite	0-20	Miliolite	0-18						
							Gravels	0- 6						
		PLIOCENE - MIOCENE				-	Hofuf	0- 6	Upper Dam	20	Hofuf	-	-	-
							Dam	0- 6			Dam	Upper	-	50
									Lower Dam			Lower	-	30
	PALEOGENE	EOCENE	Middle	Dammam Group	Abarug Bed	2	Abaruk Bed	2	Alat Lst	24	Dammam	Upper	Abarug Dolomitic Limestone	2
					Abarug Chalk	11	Abaruk Chalk	11	Alat Marl	12			Abarug Marl	10
					Surface Dolomite	24	Surface Dolomite	24	Simsima	8			Simsima Dolomite & Limestone	10-30
					Simsima Chalks	9	Simsima Chalks	9						
			Lower		Alveolina Beds	1	Alveolina	2	Alveolina Zone	5		Lower	Dukhan Alveolina Lst.	0-1
					Midra Shale	0-3	Midra Shales	0-3	Midra Shale	3			Midra & Saila Shales	0-10
													Fhaihil Velates Limestone	0-1
					Rus Chalks	55	Rus	30-80	Rus	80-113	Rus	-	-	28-112
		PALEOCENE			Umm er Radhuma	-	Umm er Radhuma	275-300	Umm er Radhuma	335-370	Umm er Radhuma	-	-	-

				(M)	(M)		
QUATERNARY							
Holocene	-	-	-	-	-	Mobile sands, bioclastic beach deposits, soils	Unimportant except as recipients of recharge and outflow discharge to the sea
Pleistocene	-	-	-	1	? 20	Fixed dune sands, siliceous and dolomitic, sabkha deposits, depression soils, cemented beach rocks	Conduits for evaporation losses Depression infill reducing recharge
TERTIARY							
Pliocene	-	-	-	-	-	Absent	
Miocene	Hofuf	-	-	Abs	1 - 10	Residual gravels and siliceous sands	Unimportant
- upper							
- lower	Dam	Upper Dam	-	Abs	80	Alternating beds of yellow and pink marl chalk and limestone, soft and clayey. Some gypsum. Outliers only	Unimportant as isolated outliers
		Lower Dam	-	Abs	30	Fossiliferous marls, clays and thin limestones. Outliers only. Green and red clay facies in south west.	Acts as confining aquiclude to Abarug aquifer in south west.
- lower	Hadrukh	-	-	-	-	Absent	
Oligocene	-	-	-	-	-	Absent; major unconformity	Period of diagenetic alteration of Simsima Limestone to Dolomite enhancing permeabilities.
Eocene	-	-	-	-	-	Absent; major unconformity	
- upper							
- middle	Dammam	Upper Dammam	Abarug Dolomitic Limestone	Abs	2 - 25	Grey-brown, hard, friable dolomitic limestone. Outliers only except in S.W.	Important artesian aquifer in Abu Samra area. Unimportant elsewhere.
			Abarug Dolomitic Marl	Abs	10	Soft, white to yellow clayey dolomitic chalky marl. Outliers only except in S.W.	Important supportive aquiclude in Abu Samra area. Unimportant elsewhere.
			Simsima Limestone and Dolomite	10	30	Originally, very variable but basically chalky limestone. Diagenetic dolomite replacement of variable thickness up to 10m though general	Forms 80% of Qatar land surface Both facies important aquifer where phreatic levels near surface in coastal belt etc.
	Dammam	Lower Dammam	Alveolina Limestone	Abs	1	E_1 marker; white compact fossiliferous chalky limestone	Lower Dammam consisting largely of shale, has confining influence on Rus groundwater. Absence from northern $\frac{1}{3}$ of Qatar of great recharge significance and controlling factor in removal of gypsum from underlying Rus Formation

Table 3.4

AGE	FORMATION	SUB FORMATION	MEMBER	APPROXIMATE ARCH (M)	THICKNESS TROUGH (M)	LITHOLOGY	HYDROGEOLOGICAL SIGNIFICANCE
Eocene - middle	Dammam	Lower Dammam	Midra Shale	Abs.	10	Laminate, sub-fossile brown-yellow shale. Fossiliferous (sharks teeth) and with limonite and phosphate nodules.	(see above)
			Fhaihil Velates Limestone	Abs.	1	White crystalline compact fossiliferous limestone.	
- lower	Rus	-	Unit - 1 "Chalky Limestone"	10	20+	Two main facies.	Anhydrite facies aquiclude, Carbonate faices, important aquifer containing large reserves of fresh water and in hydraulic continuity with Umm er Radhuma Formation below.
			Unit - 2 "Anhydrite"	10	100	Sulphate, thick; anhydrite up to 50% with marl and some thin limestones.	
			Unit - 3 "Dol. Limestone"	Abs.	?Abs.	Carbonate, thin; limestone, dolomite and some marl. May be due to non-deposition over positive areas or removal of gypsum and consequence collapse. Variation occurs in Unit 2.	
Palaeocene	Umm er Radhuma	-	-	300	?500	Thick, alternating sequence of limestones and dolomites. Top 30-50 m karstic dolomite. Marl content increasing downwards.	Upper unit excellent aquifer of very high yield and porosity. Remainder variable.
				Total thickness known only from Dukhan anticlinal area.			

Table 3.4 (cont'd)

.2| le Ruwais 1A (Almojil) cont'd

	Thickness (m)
om te, granular, friable and Limestone, white,	6
es one, white, fine grained,	3
omite and Limestone, as above,	1.5
s one as above,	3
om te and Limestone, as above,	17
estone, cream, fine grained,	5
ickness not penetrated	35.5 m

3 Tertiary Succession - Palaeogene

.3.1 Umm er Radhuma Formation - Palaeocene

e Umm er Radhuma was first defined by Henry and Brown (1935) in an unpublished ARAMCO iy and subsequently quoted by Steineke and Bramkamp (1952). Outcrop type sections are in i rabia in the vicinity of Umm Radma and in the wādī al Bātin. In Qatar the Umm er .ar was first described by Sugden (1956) in oil well logs and the formational name was ted in the re-interpretation of old logs going back to 1940. Micro-faunal evidence :a es that the lower part of the Umm er Radhuma is Palaeocene in age with the upper part f Lower Eocene age, (Smout, 1954).

A though the Umm er Radhuma conformably overlies the Aruma Formation, the Palaeogene was i d of major marine transgression extending over the Arabian Gulf area through to the ern Mediterranean. Deposition was associated with minor folding along northerly trending resulting in regional and local facies differences. These axes are probably related to le eloping mobility of thick salt deposits of Palaeozoic age at considerable depth below accumulating thickness of geosynclinal sediments. As the deformable evaporites flowed ccreted, their specific gravity, which was lower than the surrounding rocks, created an d hrust which resulted in fracturing, folding and upward bulging of the overlying layers he salts migrated into higher strata. Such folds have persisted throughout the Tertiary sitional history and lithological variation and reduced thicknesses over positive areas l rly evident. In north-eastern Saudi Arabia argillaceous, with subsidiary calcareous es ere deposited. Elsewhere, including Qatar, calcareous facies deposition dominated considerable thicknesses of calcarenite and porous detrital limestones, although locally, b diary, areas, some argillaceous sedimentation occurred and gypsum, indicating shallow- aporitic conditions, is also recorded. Dolomitisation has occurred at all levels in Jmm er Radhuma of the Gulf area. X-ray diffraction analysis of powdered rock samples has a d the total absence of calcium carbonate from a typical Umm er Radhuma sample 3 ' - 350' depth). Calcium magnesium carbonate forms 100% of the sample.

In Saudi Arabia the Umm er Radhuma thickness ranges from less than 300 to 700 m (GDC, . In the type section of the wādī al Bātin, 243 m are assigned and the formation consists ght coloured, aphanitic, detrital and chalky limestones and dolomites with some calcar- in the upper part. Locally it is silicified and chert occurs sporadically throughout. ty e section represents the subsiding zone argillaceous facies.

In Bahrain, the thickness ranges from 115 to over 300 m and has been subdivided into u ts.

ight brown or cream, dolomite and dolomitic limestones with some siliceous, very hard, lu gey dolomite which is moderately resistive on log records.

ight brown, earthy, granular, dolomitic limestones and granular friable calcarenites. ome very hard blue-grey dolomite also occurs. Well developed jointing is recorded and og ng suggests large groundwater flows.

c. Grey brown, vesicular, dolomitic limestone, increasingly argillaceous downwards. Low resistivity on logs with higher gamma ray counts than either a/ or b/.

In Qatar, where there are no outcrops of the Formation, the full thickness of the Umm er Radhuma has only been penetrated by three water exploration boreholes (Amojil, 1963) and it was found to range from 270 m to 370 m thick. Detailed lithological descriptions of the whole unit are therefore limited but general facies inferences may be drawn. The following descriptions for boreholes 1A and P22a are typical of the lithology of the central area of the peninsula.

Umm er Radhuma Lithological Description

Borehole Ruwais 1A (Almojil)

Base of Rus Formation

	Thickness (m)
Limestone, dolomitic, off-shite granular	23
Lost circulation	14
Limestone, as above	14
Limestone, as above, with dark grey, crystalline dolomite	3
Limestone, as above	4.5
Dolomite, white, fine-grained, friable, vesicular	4.5
Limestone, as above	3
Dolomite, grey, friable, granular, some limestone	3
Lost circulation	48
Siltstone	1
Lost circulation	240
Top of Aruma Formation	358 m

Borehole P22A

Base of Rus Formation

	Thickness (m)
Dolomite, chalky limestone and marl	18.5
Dolomitic marlstone	12
Dolomitic limestone	4
Chert, with dolomitic limestone	2
Dolomitic limestone	21
Hard vesicular dolomite	7.5
Very hard, vesicular dolomite	6.7
Dolomitic marl and vesicular dolomite	36.8
Full thickness not penetrated	108.5

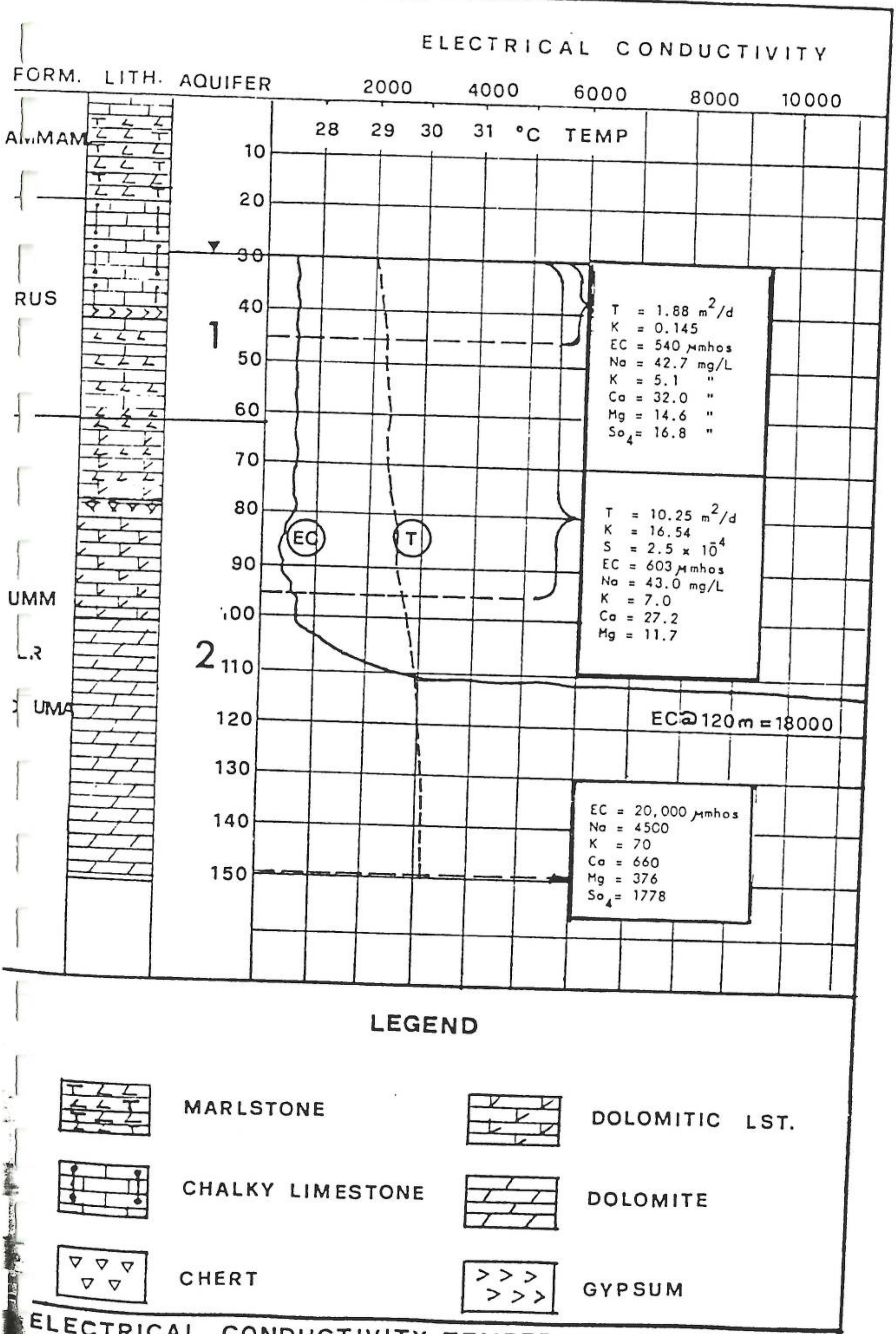
The results of the geophysical logging of P22a with a comparative lithological column are presented as Fig. 3.4.

The upper contact with the Rus is marked by an abrupt lithological change from grey brown, vesicular, dolomitic limestone to the cream or near-white chalky limestones of the Rus Formation above.

The lithology of the Umm er Radhuma Formation of Qatar is vesicular dolomites and dolomitic remarkably uniform and limestones are found throughout the major part of the peninsular and in the Dukhan area.

Argillaceous and gypsiferous material is believed to occur to only a minor extent in these areas and towards the base of the unit.

In the large number of boreholes which partially penetrate the Umm er Radhuma in the central part of the peninsula, argillaceous material is only rarely present. However, lost



ELECTRICAL CONDUCTIVITY, TEMPERATURE AND HYDROCHEMICAL PROFILES IN WELL No. P22A circulation problems during drilling in the Umm er Radhuma may mask the true representation of the lithologies.

A different situation may be noted in borehole PS-02U in Saudi Arabia (Fig. 3.5)[1]. This borehole, which is sited adjacent to the Gulf of Salwa, shows an important incidence of shales and it is located on the western flank of a subsiding area. A similar condition occurs at borehole P29b north-west Qatar, which penetrated 95.7 m of the Formation, circulation was lost completely at the contact between dolomitic limestones, with abundant gypsum, of the Rus formation and harder, grey brown vesicular dolomite with quartz of the top of the Umm er Radhuma. Coring and casing permitted the intermittent recovery of fawn and grey, marly mudstones, dolomitic limestones and dolomite which form the remaining 90 m of the cut section.

The lithology is listed in the following table and the results of geophysical logging form Fig. 3.6.

<u>Umm er Radhuma Lithological Description</u>

<u>Borehole P29b</u>

<u>Base of Rus Formation</u>

	Thickness (m)
<u>Dolomitic</u> <u>limestone</u>, hard, brown with abundant white crystalline quartz	
Lost circulation	0.75
Cored section. 33% recovery. Marly <u>dolomitic</u> <u>limestone</u>, with slaley	5.3
<u>mudstone</u> and foetid black clay	3.7
Cored section 30% recovery. Hard, marly, fawn <u>dolomitic</u> <u>limestone</u>.	
Abundant comminuted quartz.	4.3
No recovery	
Cored section 87% recovery. Marley domolitic <u>limestone</u>, <u>mudstone</u> and shale grey, hard to soft and shaley	22.5
Marly <u>limestone</u> and marl, soft grey to fawn. Black mudstone streaks	
No recovery	10.7
Cored section 100% recovery. Calcareous and dolomitic <u>mudstone</u>, soft,	42.7
Olive grey.	4.3
Black marl and some gypsum	
<u>Total Depth. Full thickness not penetrated</u>	95.8

It thus appears that an argillaceous facies of the Umm er Radhuma was deposited in the subsiding areas between the Qatar pericline and the Dukhan anticline. Borehole Almojil 3A at Qarn Abu Wajil penetrated over 300 m below the top of the Formation but cuttings were recovered from the top 13 m only. At site P34, also in south-west Qatar, the top 17 m of the Umm er Radhuma Formation consisted of soft beige to buff argillaceous dolomitic limestones. Circulation was lost below this depth and intermittent recovery of cutting revealed the typical lithology of grey-brown dolomite and dolomitic limestone.

Thus it would appear that the Gulf of Salwa area was, in Upper Umm er Radhuma times, a slowly subsiding area into which considerable amounts of argillaceous material were transported. Although lithological facies evidence for the Umm er Radhuma formation in Qatar is sparse, information from Saudi Arabia, sedimentary data from younger stratigraphical units in Qatar (see Rus Formation) and the structural character of the country suggests a possible facies distribution for the Umm er Radhuma formation similar to that portrayed in Fig. 3.5.

The hydro-geological importance of the Umm er Radhuma in Qatar lies in the upper 20 to 100 m of the formation. In the Project drilling programme therefore only this upper section was penetrated for groundwater information although limited rig capacity has also restricted drilled depths. A correlation of the lithological information obtained is shown in Fig. 3.7.

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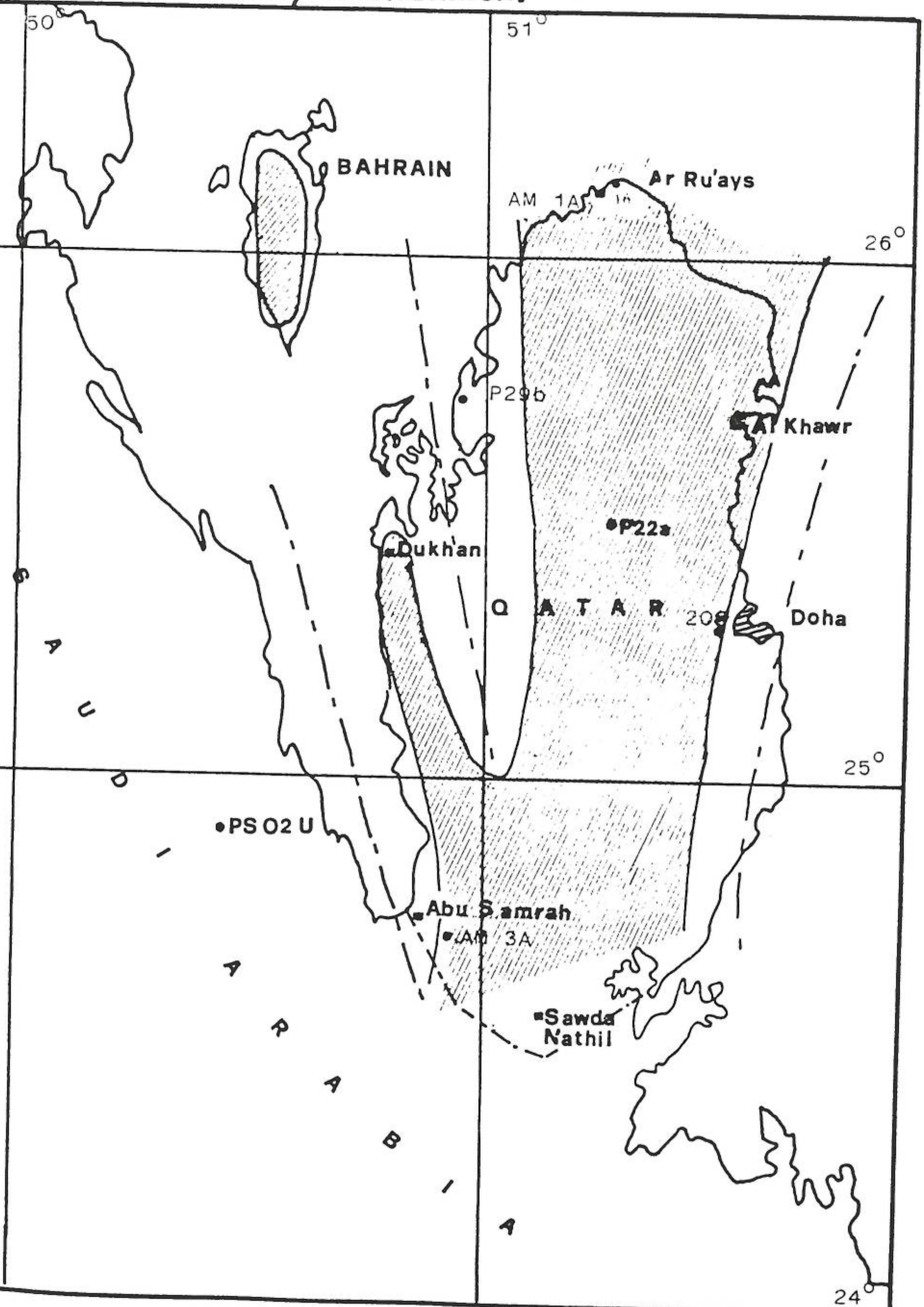
[1] Data provided by the Ministry of Water and Agriculture, Saudi Arabia.

ocene: Sedimentary Environment

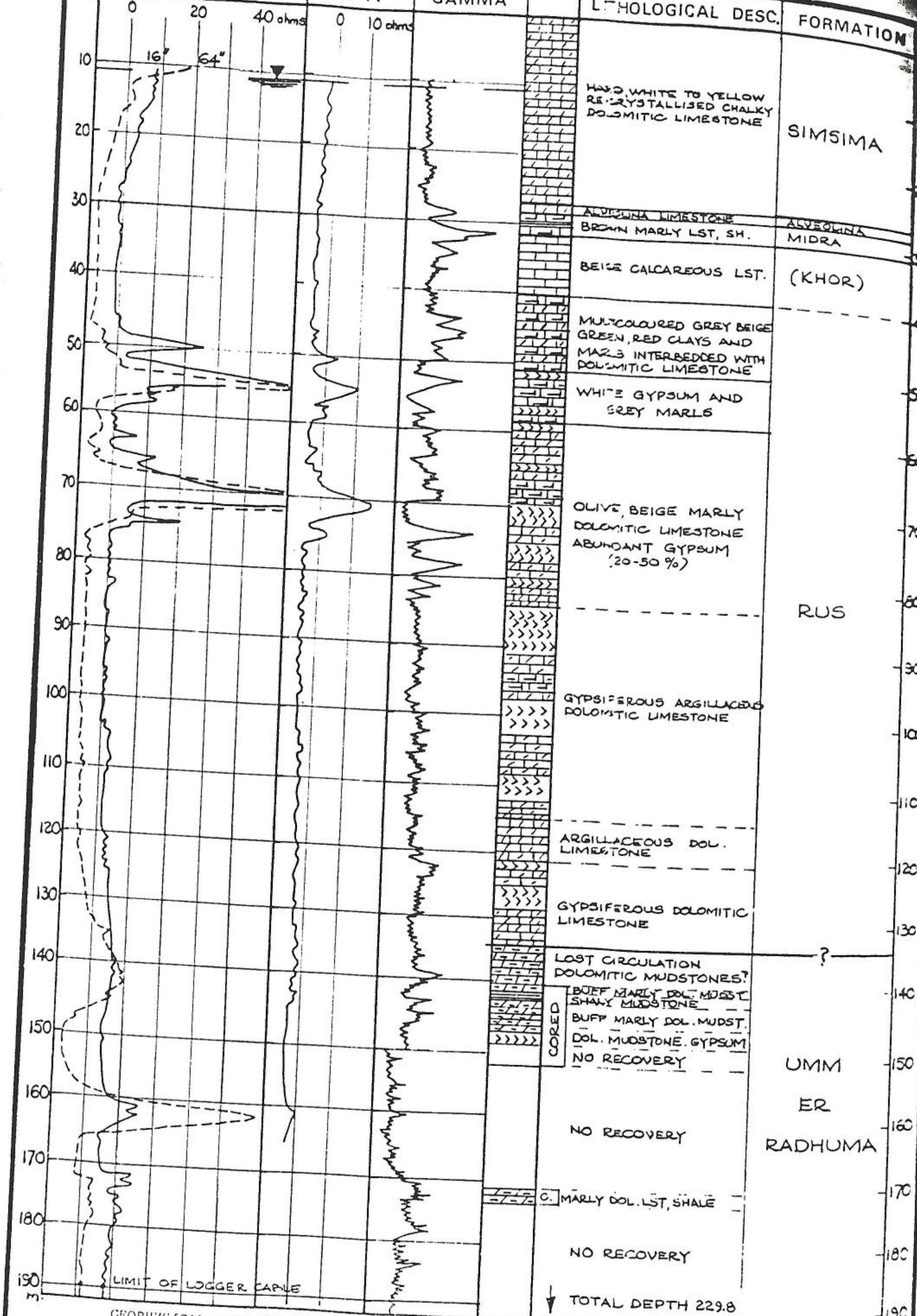


Stable area of relatively slow, clear-water sedimentation

Subsiding area of relatively rapid, turbid, evaporite sedimentation.

Axis of subsidence sedimentation

Fig. 3.5



GEOPHYSICAL LOGS AND LITHOSTRATIGRAPHICAL CORRELATION

Fig. 3.6 P29

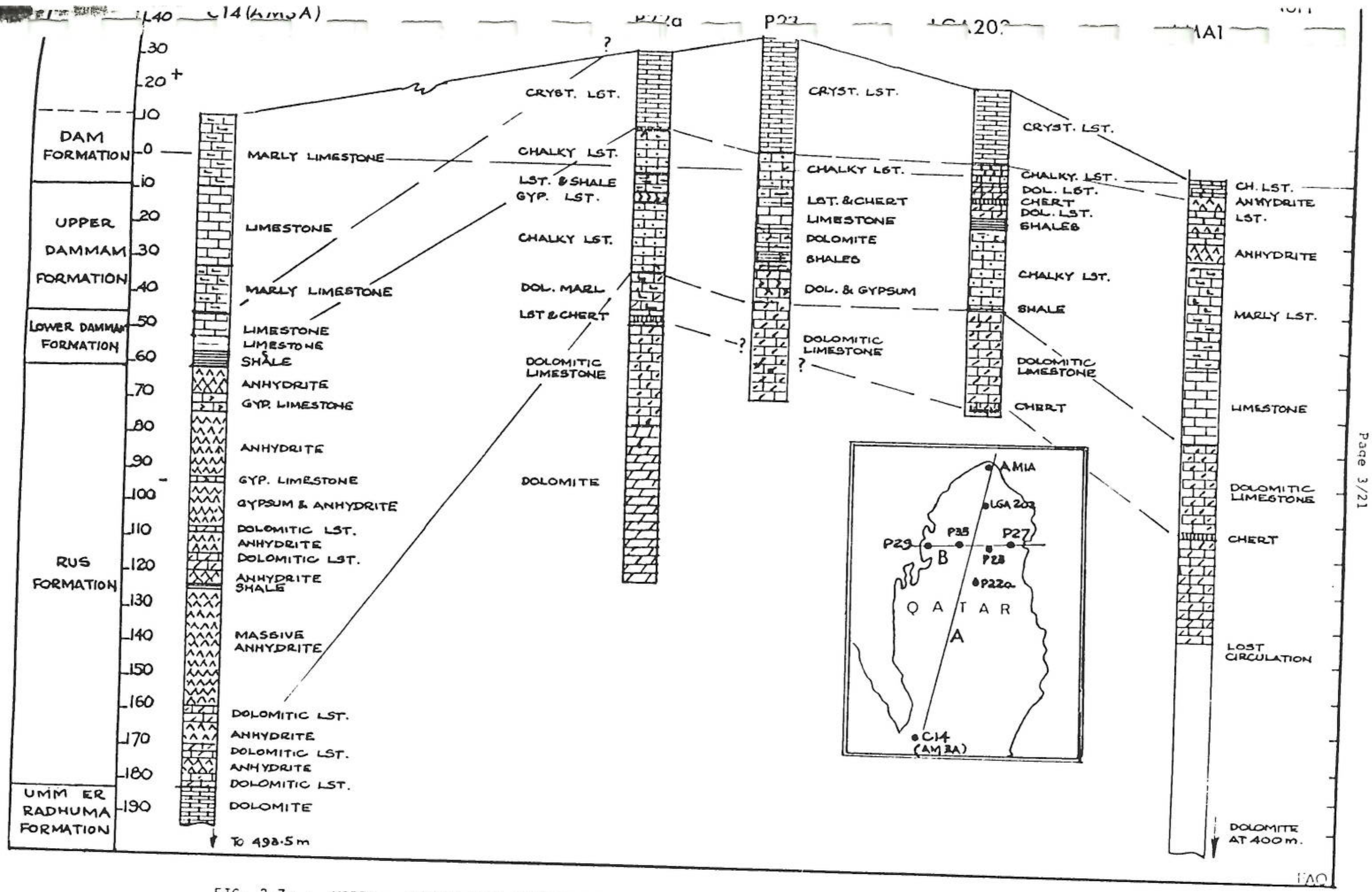


FIG. 3.7a - NORTH - SOUTH LITHO-STRATIGRAPHIC CORRELATION - Vert. Scale 1:1000 , Hor. Scale 1:300,000

3.7a

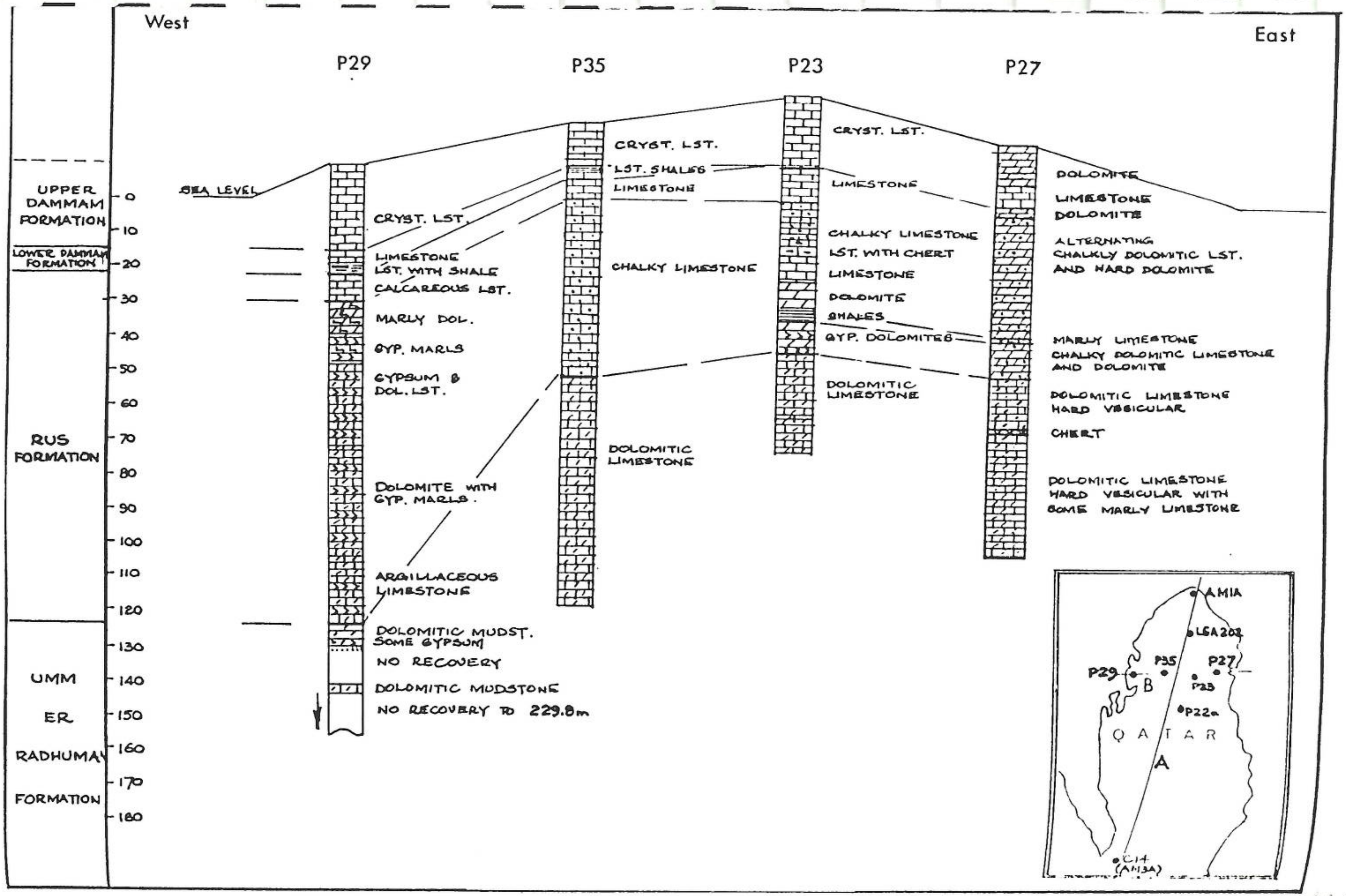


FIG. 3.7b - WEST - EAST LITHO-STRATIGRAPHIC CORRELATION - Vert. Scale 1:1000 Hor. Scale 1:200,000

3.7b

Although the Umm er Radhuma underlying central Qatar is generally a uniform dolomite s ;uence siliceous zones do occur in the form of chert and silicified limestone or dolomite. Project drilling records show the presence of such a zone some 15-20 m below the top of the f mation in north eastern Qatar bounded by an arc extending from Jebel Fuwairat-Al Majidah-Al Otoriyah to Doha. The area within which a conspicuous chert horizon occurs and the depth below sea level is shown as Fig. 3.8.

3.2.3.2 Rus Formation - Lower Eocene

The Umm er Radhuma Formation is overlain by the Rus Formation. The formational name 'as first used by Bramkamp for a type section in the Umm er Ru'us area of Saudi Arabia and r roduced into the literature by Thralls and Hasson (1956). The same nomenclature was adopted for Qatar by Sugden (1956) and for Bahrain by Willis (1967). Diagnostic fossils re not known to occur in the Rus Formation although it is underlain and overlain by beds f proven Lower Eocene age (Cavalier, 1970).

The contact between the Umm er Radhuma sequence and the Rus Formation in many areas s brupt. In Qatar it is characterised by the disappearance of a marine fauna and generally by facies change. However, as described below, facies similarity and post-depositional dissolution processes pose certain difficulties in establishing the formational contact lly.

Sander (1962) reports Saudi Arabian fossil evidence from the basal Rus Formation beds h indicates a shallow marine depositional environment. The abrupt facies change into Rus Formation over much of the area suggests a possible sedimentary haitus after the eposition of the Umm er Radhuma. Evidence from Saudi Arabia (BRGM, 1977) indicates that e hiatus was associated with uplift and land emergence in some positive structurally r olled areas.

With the continuation of sedimentation, the Rus Formation appears to have been deposited shallower sea than the Umm er Radhuma. The distribution of facies in the Rus Formation nd the thickness variation of the unit, however, show that the depositional environment s variable over Qatar and it is believed that sedimentation was controlled by gentle r tural movements. Deposition in warm, shallow, clear water occurred in areas of positive tructural influence resulting in relatively thinner, purer limestones and relatively icker turbid and evaporitic sedimentation occurred in the structural negative areas. The d increase in the thickness of the Rus Formation deposits from the structurally high e structurally low areas suggests that compensatory epirogenetic subsidence was occurr- g at the time of deposition. The regional distribution of the different depositional onments is shown in Fig. 3.9. The structural influences are believed to have persisted the beginning of the Tertiary and possibly earlier.

n Saudi Arabia, the type section of the Rus is some 56 m thick and has been subdivided f lows :-

Lithology	Thickness (m)
t soft, porous chalky <u>limestone</u> with calcarenite at the top	3.5
ght coloured <u>marls</u> with <u>gypsum</u> and thin bands of <u>limestone</u>	31.5
y o buff compact crystalline <u>limestone</u> commonly partly dolomitised	21.0

This sequence is not typical of the sub-surface Rus where it ranges from over 100 m of s e anhydrite with thin interbedded limestones and calcarenites to the very thin, 10 m, re dual carbonate left after the solution of the sulphates. In non-sulphate areas the is very difficult to recognise from cuttings only.

Umm er Radhuma Formation: Chert Horizon

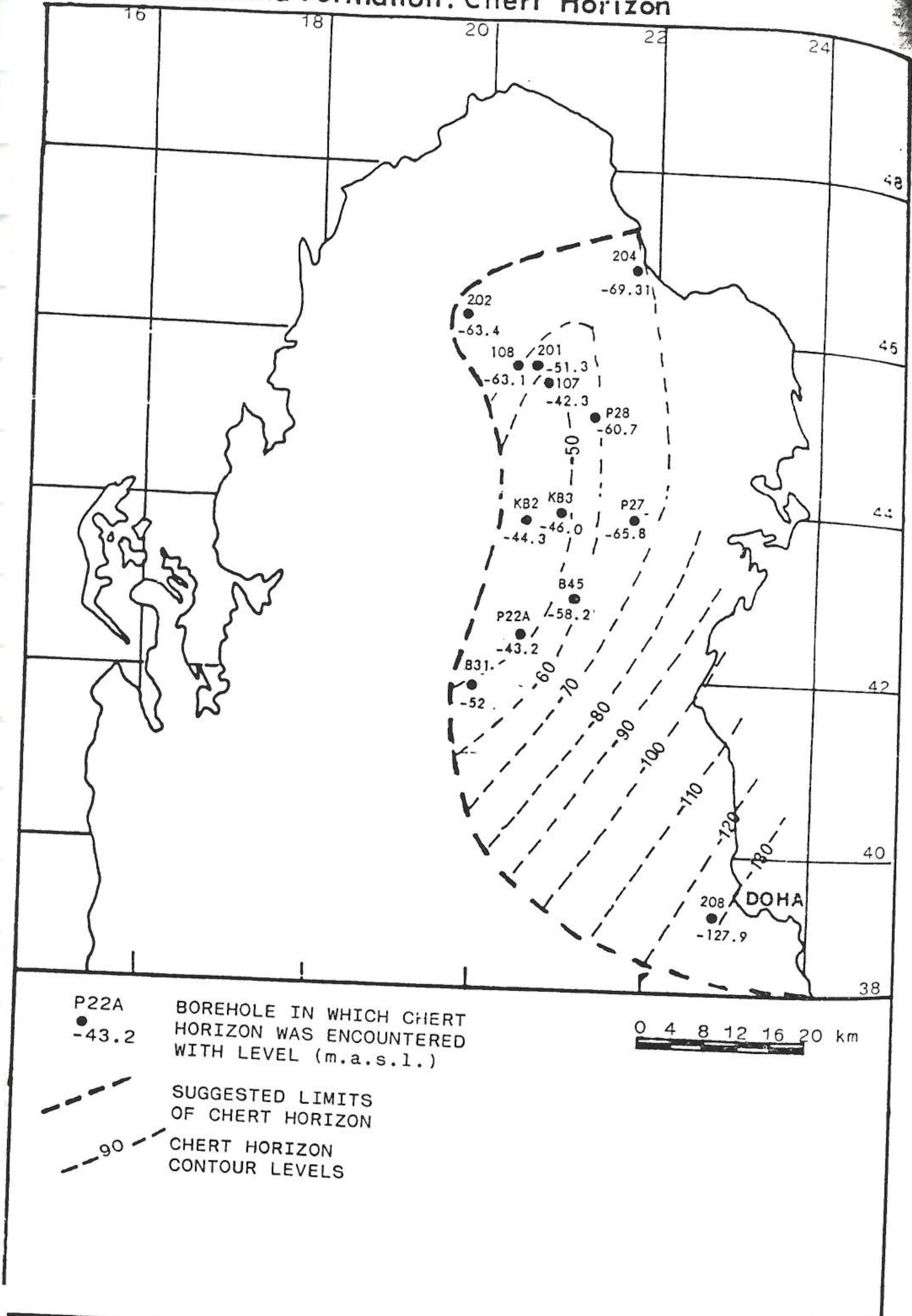


Fig 3.8

ower Eocene : Sedimentary Environment

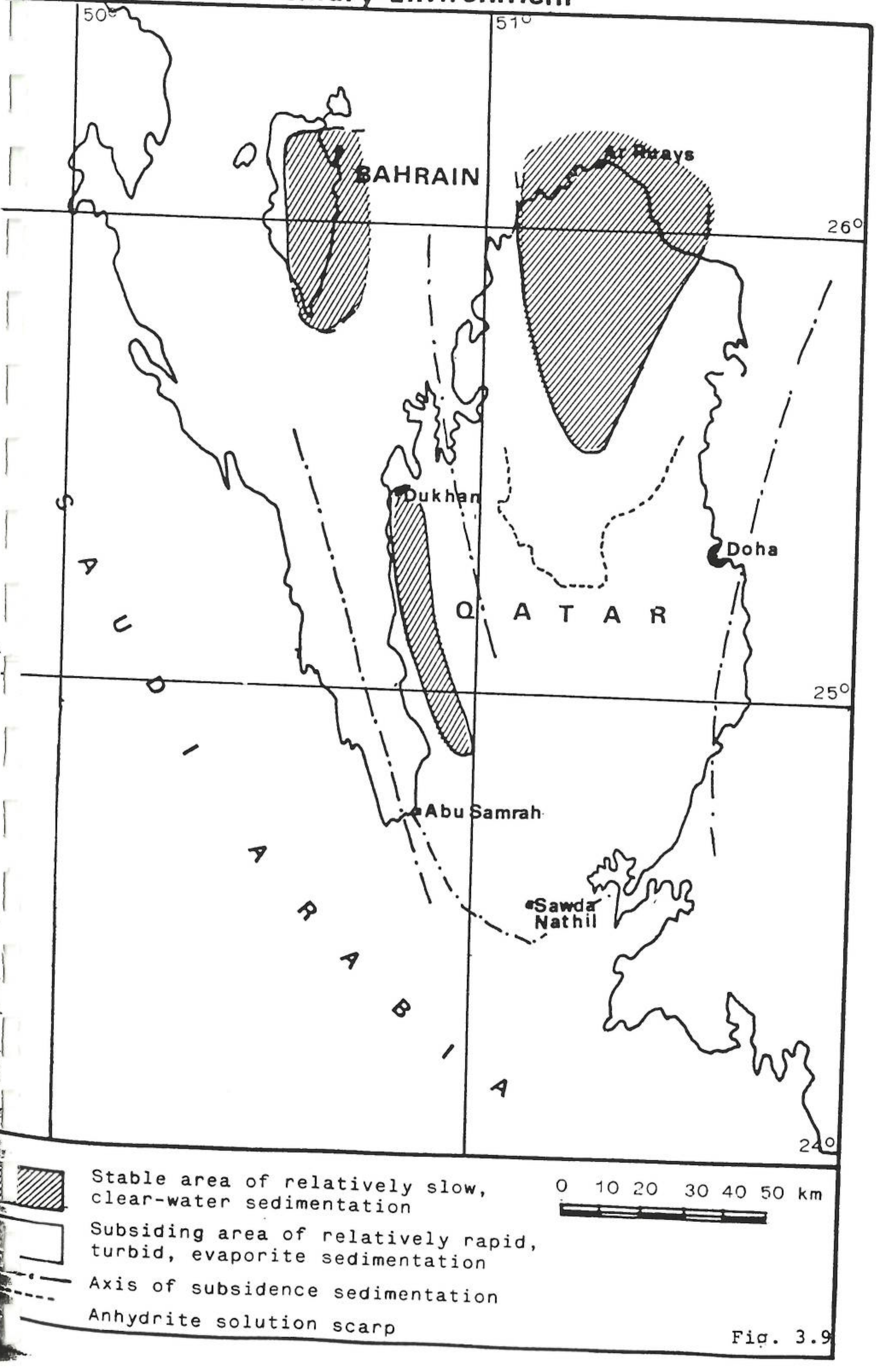
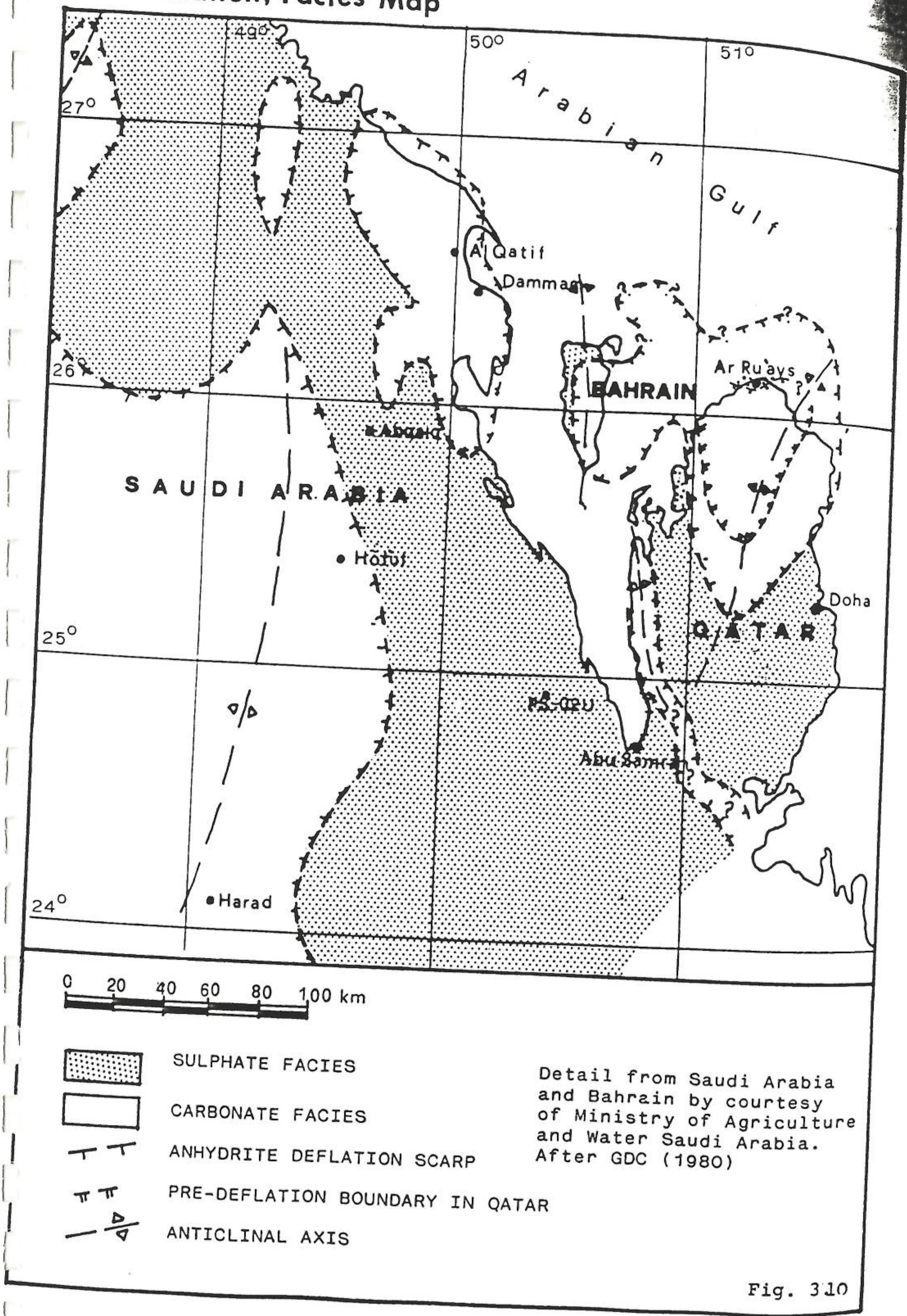


Fig. 3.9

Rus Formation; Facies Map



Detail from Saudi Arabia and Bahrain by courtesy of Ministry of Agriculture and Water Saudi Arabia. After GDC (1980)

Fig. 310

Where anhydrites occur in both the Umm er Radhuma and the Rus in the northern area, e boundary is fixed arbitrarily where the anhydrite ceases to be dominant.

For Bahrain, a complete section consists of a minimum of 50 m of chalky dolomite lime- one, shale, anhydrite or gypsum. This may rise to over 100 m with a thickening of the psum. As elsewhere, thin, dominantly carbonate, facies occurs over positive dome area and the Formation thickens with increasing clay and anhydrite from the stable area to the eas of gentle subsidence. Anhydrite occurs generally to the north and west of Bahrain land where the anhydrite may be 25% of the thickness and the combined anhydrite and clay over 50%.

The variable mode of deposition of the Rus Formation has led to two major facies being present in Qatar; these are a gypsiferous, argillaceous, facies termed the <u>Sulphate Facies</u> and a calcareous facies on <u>Carbonate Facies</u>. Although the distinction clearly exists on a s limentary basis, post-depositional gypsum dissolution has complicated the recognition and separation between the facies in boundary areas. Fig. 3.10 illustrates the distribution of the two facies and also indicates the southward shift to the present-day contact between the predominantly carbonate Rus of the north and the sulphate Rus of the remainder of Qatar due to dissolution of the anhydrite within the formation.

The general removal of Rus anhydrite has resulted in a deflation of the landscape and the contact between the two distinctive areas has been termed a solution or deflation scarp. Fig. 3.11 illustrates the proposed mechanism of the solution of the anhydrite and the results. F j. 3.12 illustrates the features of the numerous surface collapse structure or depressions.

It is very significant that the solution scarp has migrated southwards to be almost c ncident with the northerly limit of the shales of the overlying Lower Dammam Formation.

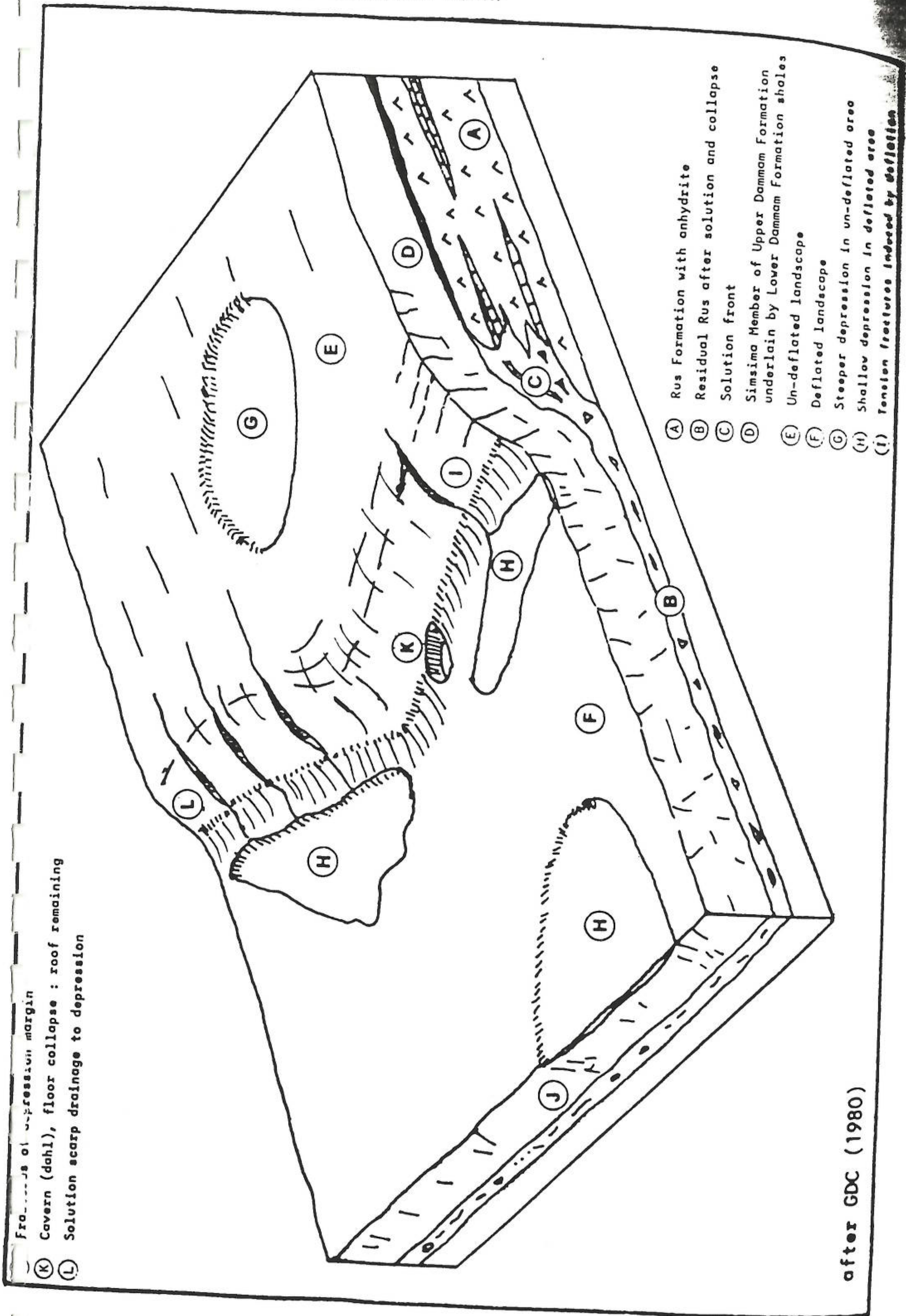
It is suggested that the presence or absence of the Lower Dammam shales and marls over- l ing the Rus Formation has exerted great influence in the dissolution process and consequently o the hydrogeology as a whole.

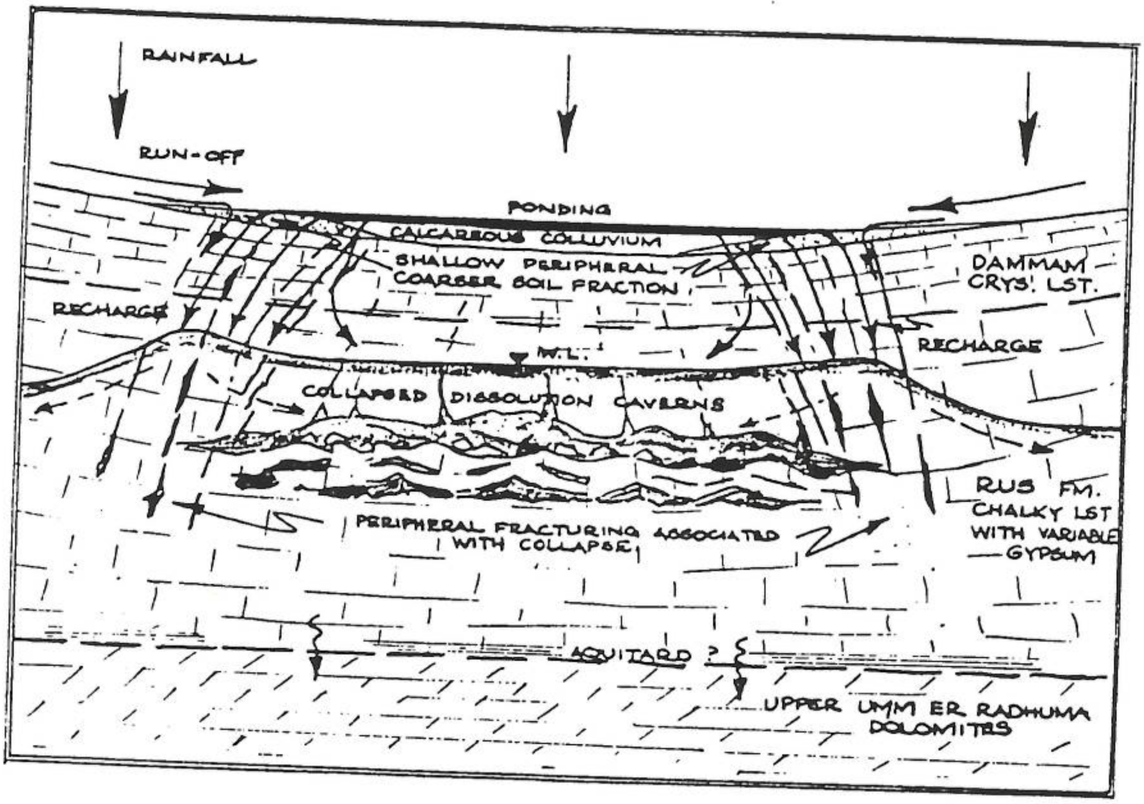
Collapse features occur in both facies areas and it is possible that the carbonate facies d tinction, which can be clearly defined in the upper part of the Formation, may not have been so well applicable in the lower part. Some of the carbonate facies area may therefore be partially attributable to the complete dissolution and removal of gypsiferous material a hough in dominantly carbonate areas in the north a worked distinction remains as there argillaceous material is also insignificant.

Although the Rus Formation underlies the whole peninsula it outcrops over a relatively small area. Enclosure 1 provides the outcrop details and Fig. 3.13 illustrates the facies areas related to the Lower Dammam limit as well as the coincidence with the results of g physical surveys and the pronounced solution scarp. In northern Qatar the main area of R Formation outcrop occurs to the north-west of Doha in the area of Umm el Khor and Al-Majidah. The best exposures of the formation occur along the Dukhan anticline in western Q ar between Dukhan and Ain Hammad, while further outcrop with abundant gypsum, the only face exposure of the Sulphate Facies, is present in the vicinity of Saudi Nathil.

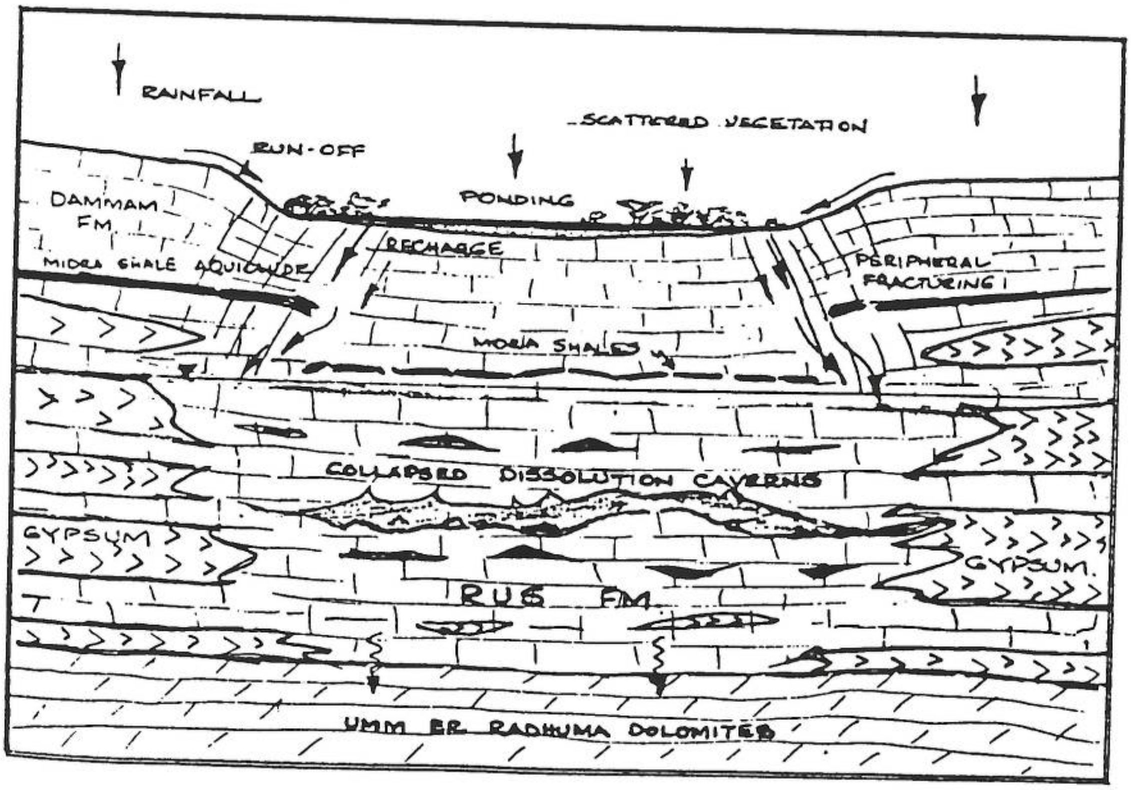
The outcrop type section for part of the Rus Formation in Qatar was established by alier (1970) at Fhaihil and the section description is reproduced in Figure 3.14. Only the upper part of the formation outcrops and the lithology is predominantly chalky dolomitic limestone with soft and hard limestones dominating and may tentatively be correlated with t 1 and the top of Unit 2 of the Saudi Arabian type locality. The section is located on structurally positive area and represents typical Rus Formation Carbonate facies. The dding in the outcrop area is not disrupted indicating that dissolution has not been ive.

FEATURES OF ANHYDRITE SOLUTION SCARP





(A)



(B)

Fig. 3.12

SKETCH CROSS SECTIONS OF TWO CHARACTERISTIC COLLAPSE STRUCTURES IN QATAR SHOWING RECHARGE MECHANISM

(A) NORTHERN RUS CARBONIFEROUS FACIES AREA,

(B) SOUTHERN GYPSIFEROUS FACIES AREA

Rus Formation Facies and Province Delineation

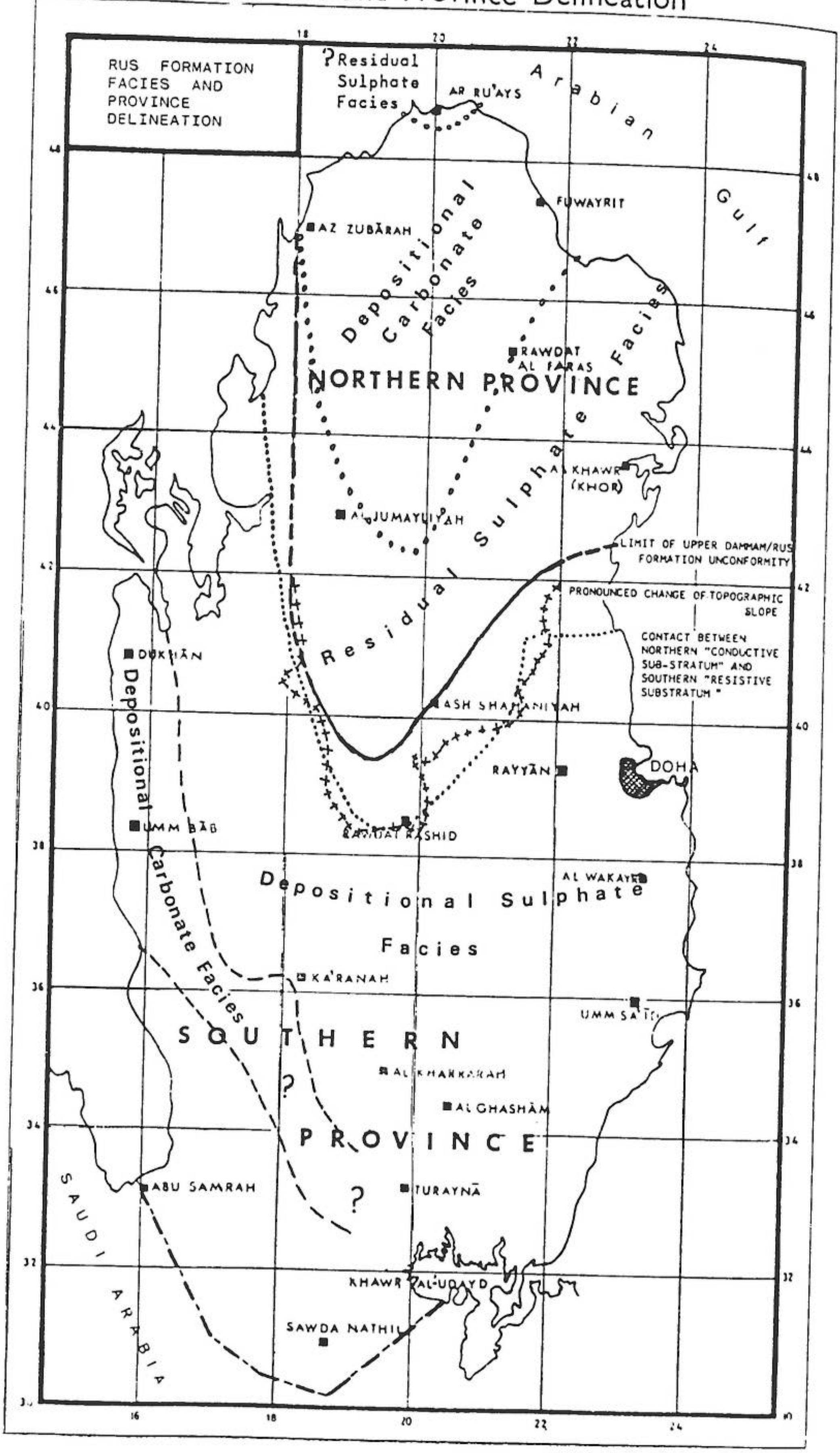
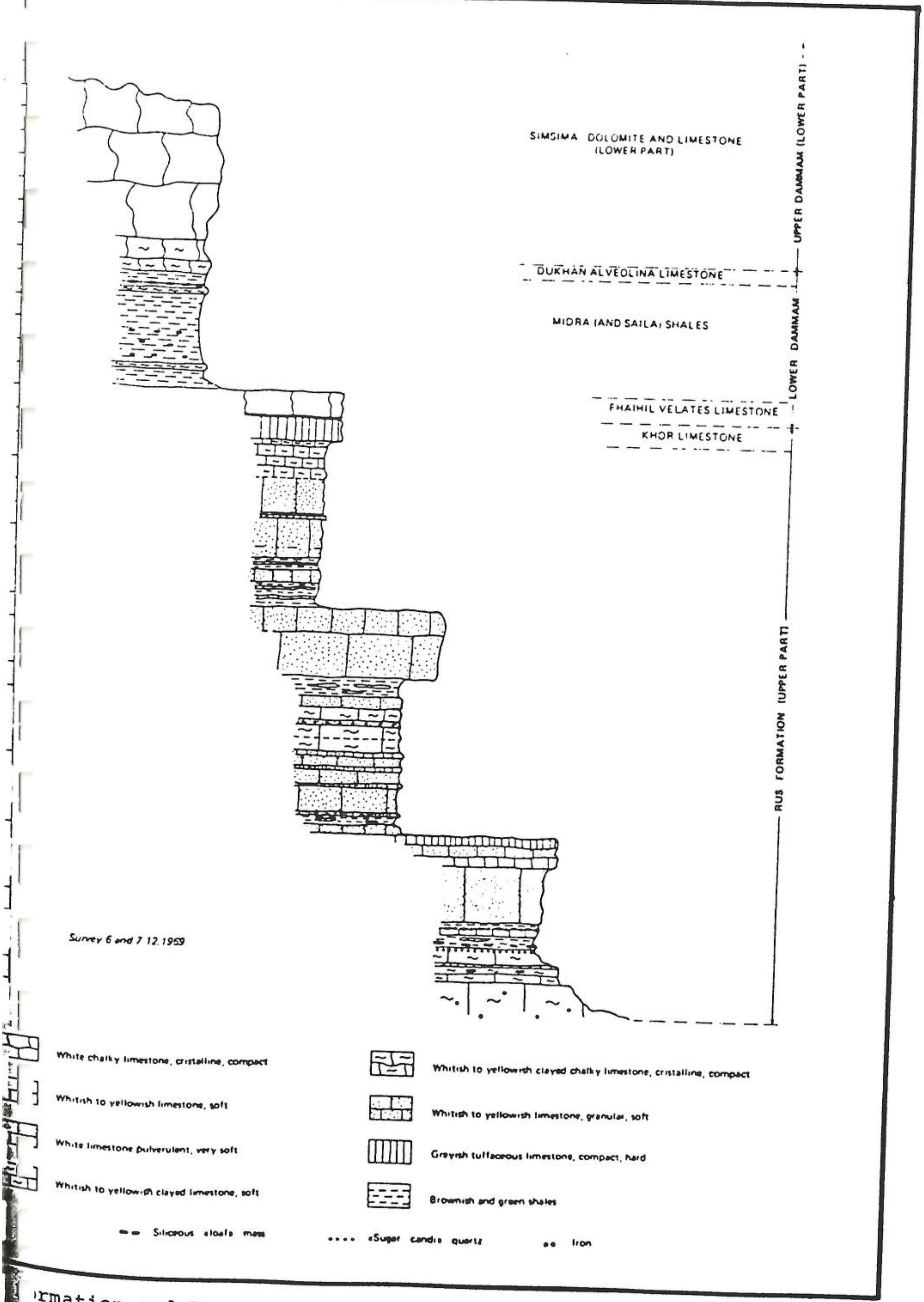


Fig. 3.13



ormation and Dammam
ion - Type. Section : 1 km east of the Q.P.C. plants in Fhaihil
(Djebel Dukhan)
(after Cavalier, 1970)

Table 3.5 gives the thickness of the Formation encountered in the Project drilling programme with an indication of area and facies.

Table 3.5

Rus Formation : Lithology, Thickness and Province

Borehole	Thickness (m)	Province	Remarks
AMIA	54.0	D.C.F.	Northernmost, anticlinal pitch
LGA203	56.7	"	" " "
LGA202	40.9	"	Anticlinal area, axial
SH9	51.8	"	" " "
SH10	43.2	"	" " "
KB2	54.9	"	" " "
LGA201	28.6	"	" " "
LGA107	43 +	"	Eastern flank
LGA108	47.9	"	" "
P24	(92)	"	Western flank. Doubtful value
P35	57.6	"	Western flank
LGA204	32.3	"	Easternmost near margin with R.S.F.
LGA205	30.5	"	Westernmost near margin with R.S.F.
P31	14.8	D.C.F.	Dukhan Structure. axial
P15	(28)	"	" " "
P34	33.5	"	" " "
P13	(36)	"	" " limb
QDH27	51 +	"	" " "
P23	40.6	DCF/RSF	Boundary area between facies
LGA207	42 +	R.S.F.	Anticlinal area, axial
KB1	40 +	"	" " "
P20	(81.5)	"	Anticlinal area, limb, thickness doubtful
P21	52.1	"	Anticlinal area, flank
P36	41.1	"	" " axial
P30	(19.3)	"	" " "
P22a	57.5	"	" " limb
B45	43 +	"	Eastern flank
P25	44 +	"	Eastern flank
P27	49.9	"	" "
P28	44.2	"	" "
KB3	61.6	"	" "
SH2a	53.8	D.S.F.	Central area
SPP/D1	51 +	"	" "
P14	(44)	"	" "
P16	(33)	"	" "
QDH28	49 +	"	" "
LGA208	78.1	"	Eastern flank
LGA206	63 +	"	Extreme western margin
P29	99.0	"	" " "

Table 3.5 cont'd

Borehole	Thickness (m)	Province	Remarks
P33	115.9	South western D.S.F.	
AM3A	121.9	" " "	
QDH25	84 +	" " "	
QDH26	58 +	" " "	

Note : D.C.F. Depositional Carbonate Facies
D.S.F. Depositional Sulphate Facies
R.S.F. Residual Sulphate Facies.

While the Rus Formation of the northern area of Deposition Carbonate Facies shows c :siderable variation in thickness with no clear control attributable to structural events t.. progressive thickening along the axis of the Dukhan Anticline, as that structure declines southwards, is clearly evident.

The thickness of the Rus also varies markedly along the structural high in the Residual Sulphate Facies area, being more uniform and somewhat thicker on the flanks.

Little information is available for the main Sulphate Facies area. Most early drilling in this area was unsuccessful in the search for potable water and few records of a .ndoned boreholes were retained. However, the thickness values recorded are consistent i . thinner axial deposition and gradual thickening both eastward and westward.

Important evidence is provided by boreholes LGA 205 (within the Depositional Carbonate a es zone) and LGA 206 (Sulphate Facies), both on the north west coast and about 10 km apart. The thickness assigned to the Rus in LGA 206 is at least twice that of LGA 205.

In the south-western Sulphate Facies area, thickening, with increasing proportions of gypsum towards the south west, consistent with the structural control over deposition in the Salwa synclinal area by the Dukhan structure, is evident.

In the surface resistivity survey carried out by the Project, major areas of highly resistive material were delineated. These areas are shown on Enclosure 3 with an illustra- i on Fig. 3.13 and are interpreted as indicating thick developments of the gypsiferous ar llaceous facies of the Rus Formation. The approximate 'V' shaped boundary between relatively high and low resistivity areas marks the limits at which the field method is a ble of identifying in depth the resistivity differences. On the basis of borehole data h 'boundary' is a zone of gradation between the two predominant facies but it does indicate the sedimentary thickening and correlation with the facies boundary and general structural a ern.

Detailed lithological information of the Rus from logs of boreholes penetrating the epositional Carbonate Facies, the Depositional Sulphate Facies, the Residual Sulphate a es and the area between the latter, are presented below.

GA 202 Representative Log of Depositional Carbonate Facies

of Dammam Formation	Thickness (m)
alk, dolomitic, brown	3.4
mite, granular, light brown	6.1
k, dolomitic, marly, white	1.5
lomite, granular, light brown	3.7
e, brown	0.6
k, dolomitic, white	3.7
le, brown	0.3
k, dolomitic, white	21.6
of Umm er Radhuma Formation	40.9 –

P29 Representative Log of Depositional Sulphate Facies

Base of Dammam Formation	Thickness (m)
Limestone, dolomitic and beige calcareous limestone	1.5
Marls and clays multicoloured grey, beige, green, red interbedded	13.7
White gypsum and grey marls	7.6
Gypsum and Olive beige marly dolomitic limestone	58.0
Gypsum and marly dolomitic argillaceous limestone	18.2
Top of Umm er Radhuma Formation (?)	99.0 m

LGA 207 Representative Log of Residual Sulphate Facies

Base of Dammam Formation	Thickness (m)
Dolomitic limestone, hard, grey/white, recrystalline, porous	2.4
Chalk, dolomitic, soft, white, powdery	6.1
Dolomite, soft white, porous, granular	1.5
Chalk dolomitic, soft white; powdery, some marl	7.6
Marl brown	0.3
Chalk dolomitic, soft, white	0.9
Dolomite, hard, white, porous, quartz nodules	2.1
Chalk, dolomitic, soft grey white	4.3
Top of Umm er Radhuma Formation	25.2 m

P23 Representative Log of Area Between Depositional Carbonate and Residual Sulphate Facies

Base of Dammam Formation	Thickness (m)
Limestone, chalky, white	9.8
Dolomite, granular with chert, light brown	4.1
Limestone, chalky, white	7.1
Dolomite, granular, with interbedded shale	5.3
Shale, dolomitic, light brown	6.8
Dolomite, gypsiferous, grey	7.5
Top of Umm er Radhuma Formation	40.6 m

From a lithological point of view the contact between the Rus Formation and the overlying Dammam Formation is relatively clear cut where the Lower Dammam shales are present. Elsewhere, with limestones present in both formations at the contact the distinction is difficult. For the purpose of this study the lithological break at the base of the Midra Shales (where they are present), (Figure 3.14), just above the actual stratigraphical contact, has adopted to define the top of the Rus Formation. Otherwise, the change from relatively hard dolomitic limestone of the Upper Dammam to softer chalky dolomitic limestone of the Rus is used.

There is generally a marked reduction in core recovery during drilling, from about 80% in the Dammam Formation to less than 50% in the gypsum bearing Rus Formation.

During drilling and in areas where the Lower Dammam shales are absent, the top of the Rus Formation may be recognised by a very marked reduction in calcium carbonate ($CaCO_3$) content and a corresponding increase of magnesium carbonate ($MgCO_3$) to about 40% from less than 5% in the chalky Simsima Limestone member above Dolomitic limestone being a double carbonate, the $MgCO_3$ component cannot exceed about 45% except in a very pure dolomite.

ognised in the Depositional Sulphate
by core drilling. Six distinct cycles

Gypsum 50% or more. Clay
content increases upward

ver ved material, deposited under reducing
:io of a biogenic or chemically precipi-
raction analysis of powdered rock samples
t of typical Rus Formation limestones
:i are generally dolomitic and not
l evaporation of the brackish water areas
asing proportions of clay towards the top
f shwater flooding of the evaporation
The reappearance to the greenish clay
ional material only and the beginning of

:ion of gypsum in each cycle upwards in the
ays and limestones.

. thickness of each cycle and therefore of
t Facies areas, post-depositional
t ility and aquifer characteristics of

o ably, by the Dammam Formation. The
r kamp for a type section on the Dahran -
by Thralls and Hasson (1956). The term
a by Willis (1967). Fossil evidence
e in age.

onsistent and widespread marine conditions
n f shallow water limestones, marls and
. The type section in Saudi Arabia is
sists of only 33 m of strata and may
s hicken markedly away from the Dammam
c established on the basis of borehole

	Thickness
mestone with	Up to 90 m
with a basal	Up to 100 m
	15 m
	15 m
	8 m

een established, the complete absence
the relatively thinner sequence else-

	Thickness	
	Crest	Flank
imestone	Absent	15 - 25 m
	Absent	9 - 15 m
ite	Absent	30 - 39 m
	Absent	NR
	Absent	~ 10 m
imestone	Absent	8 - 20 m

ormation into five members, separating
division of Upper and Lower Dammam
l those in Bahrain and Saudi Arabia
part of the sequence at Fhaihil is
ion for the upper part of the sequence
not always distinguishable lithologi-

arly recognised by the change from
tion.

ncountered in outcrop and drilling

Lithology	Thickness	
	Crest	Flank
porous, buff dolo- ıd dolarenite	Absent*	2 m
ff white, dolomi- l	Absent*	10 m
olomitised, chalky ne	10 m	30 m
ite chalky limestone	Absent	1 m
ellow shale and marl	Absent	10 m
chalky dolomitic ne	Absent	1 m

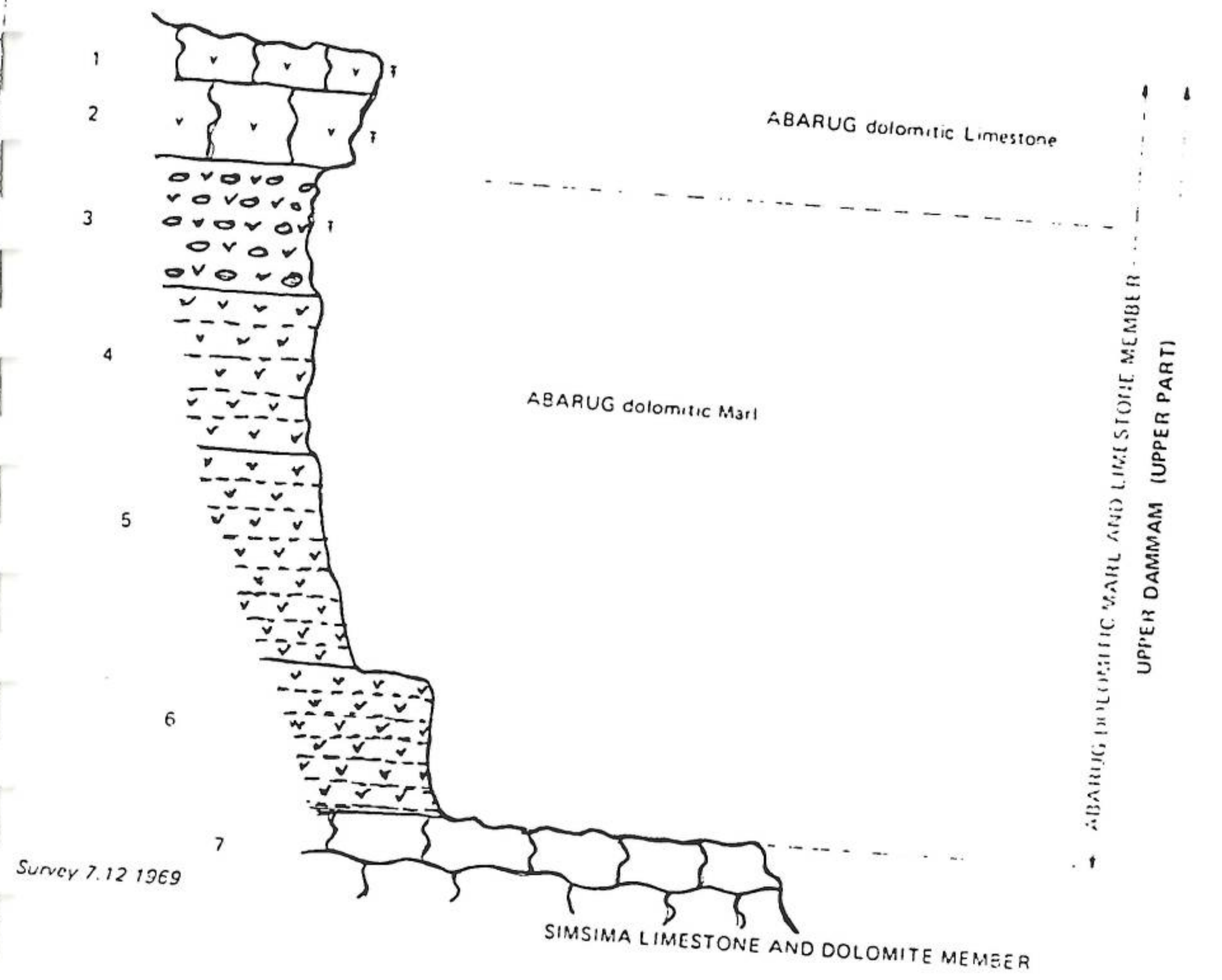
osion not certain.

n the north and north-east, and most
he principal outcrops are generally
to the underlying Rus Formation.
anges of lithology and thicknesses

5m

0m

Up:



Yellowish grey dolomite (C = 8 %, D = 85 %), hard, cristalline, massive, fossiliferous	
B[illegible]wnish grey dolomite (C = 8 %, D = 88 %), hard to soft, nodular, fossiliferous	on 0.40 to 1 m
Greyish clayed dolomite (C = 5 %, D = 75 %), hard, compact, nodular (conglomeratic aspect)	1.20 m
W[illegible]ish clayed dolomite (C = 3 %, D = 78 %), including greenish dolomitic clay (C = 3 %, D = 13 %), co[illegible]pact, rather hard, nodular	2 m
Greyish to yellowish clayed dolomite (C = 3 %, D = 64 %), compact, rather soft	2.50 m
Ye[illegible]wish brown dolomitic marl (C = 5 %, D = 49 %), compact, rather hard	3.30 m
Wh[illegible]sh to brownish chalky limestone (C = 98 %, D -), cristalline, compact, vacuolar, fossiliferous	2.60 m
	on 1.50 m

No[illegible] : C = calcite ; D = dolomite

[illegible]am Formation :Type section : 3 km south of Bir Zekrit

(after Cavalier, 1970)

Fhaihil Velates Limestone Member

Whitish, crystalline, compact, hard and fossiliferous limestone generally consistent over the whole of Qatar and about 1 m thick.

Midra (and Saila) Shales Member

The formerly subdivided units are now recognised as one unit of shales with interbedded thin limestones lying between the Fhaihil Velates Limestone and the Alveolina Limestone and formed by up to 10 m of yellow-brown to greenish grey attapulgite shales with a variable limestone content and with lenticular phosphatic nodules and intercalations, especially near Saudi Nathil. Secondary black iron oxide concretions (pseudomorphs) of pyritic (cubic) shape are abundant locally.

Dukhan Alveolina Limestone Member

This important reference horizon E_1, used in regional correlation because of its widespread and consistent nature, consists of up to 1 m of massive white limestone with abundant casts and moulds of the large nummulitic foraminferan Alveolina elliptica. The limestone has a variable clay content and is sometimes nodular. The fossils, whether whole or fragmented, can generally be recognised in drill cuttings making it a valuable reference level for subsurface correlation.

The Upper Dammam Sub-Formation

This unit is poorly defined in Qatar because of the nature of the distribution of the Simsima. While this one member forms up to 80% of the 'hard-rock' surface of Qatar, no continuous complete outcrop section has been located to provide an overview of this very important subdivision.

Simsima Limestone and Dolomite Member

Up to 30 m thick in the extreme north of the peninsula, away from the central arch and near Umm Bab, deposition of limestone and dolomite was thinner in the clearer water conditions over the arch. Subsequent erosion has removed considerable material over most of Qatar.

Three distinct facies can be recognised which may have an original (pre-dolomitisation) stratigraphic relationship of an offlap type tending northwards.

- Above, a flaggy grey to white limestone with intercalated chert bands and soft chalk. The softer material weathers out leaving residual angular to sub-angular gravel, consisting principally of chert and very hard cherty limestone. This facies is typical of the mid-west and northwestern areas.
- The middle and principal unit consists of white-buff-pink indurated and dolomitised limestone. Much chert occurs in nodular form with soft chalk and clay filling voids and fractures. The softer material weathers leaving residual limestone boulders and gravel with considerable chert. This forms the surface over most of Qatar.
- Below are yellowish, chalky limestones with bodies and bands of varicoloured soft clay (attapulgite). This also occurs over most of Qatar. Near Umm Bab a white granular limestone forms part of this unit and is extensively quarried for cement making.

All units are variably indurated and dolomitised down to about 10 m below the present ground surface. This may involve all units of the Member in some areas : in others unaffected limestones, chalks and clay overlie the Lower Dammam. This widespread dolomitisation gave rise to the proposal of the formation name "Surface Dolomite" (Stevenson in

ADSCO 1959) which has subsequently been discarded. Cavalier (1970) rightly avoided the anomaly by indicating that the Simsima chalky limestones were the original depositional acies and that the dolomite was a post-depositional alteration product. The duri-crust ɩeplacement or diagonesis of the Simsima chalky limestones could have taken place during Oligocene times as the dolomite emerges from beneath present-day Dam Formation outcrops. though the top of the Dam Formation is exposed today and has been since probably ..iocene times, it has not been similarly effected. The spongy desert soil, with iron staining (typical weathering products of the present climate of Qatar) could well show a ntinuing process by the reimposition of a modern erosion surface upon a pre-existing d igocene surface where the Simsima is now exposed as well as creating a new one where Rus Formation are exposed.

In the southwest, on the western flank of the Dukhan Anticline, it is possible that the Simsima Member is reduced to a mere remmant or absent altogether.

The detailed lithology of the complete Dammam Formation sequence from 27.7 m of the log of borehole P33 at Wadi El Araig in the south-western province is included below :

Re resentative Log of Dammam Formation Borehole P33

Ba ?_of_Dam_Formation

		Thickness (m)
Alu. (Abarug) Member	Limestone, chalky, off-white, with some harder dolomite	8.8
	Marl, yellow orange with soft, off-white to fawn shale and some chalky limestone	9.8
? Simsima Member	Shale, very soft, buff and chalky shale, white to yellow/brown	2.7
Du an Alveolina Member	Limestone, moderately hard fossiliferous, grey	0.6
:idra Member	Marls and shale brown, soft	5.8
Op ?f__Rus__Formation		27.7 m

Thus, 18.9 m of interbedded fawn, orange and brown soft chalky marls, with off-white o llow chalky shales (both of high clay content) occur between the base of the Abarug :lat) Dolomitic Limestone and the grey-brown harder dolomitic chalks with chert of the top e Rus Formation.

As these lithologies are typical of both the Abarug Marl and the Midra Shale, distinct- n ; difficult. However 0.6 m of harder, light grey, dolomitic limestone, the Alveolina s cognised and, if it is represented at all, the Simsima consists of 2.7 m of soft, f-white, yellow and brown very fine grained chalky shale (an atypical lithology) ned·ately overlying the Alveolina.

This supposition correlates well with the results of Borehole AM3a some 15 km to the :th. where 7.6 m of white, fine grained soft porous limestone, orginally unseparated m ne Abarug above, overlie 0.6 m of Alveolina and are themselves overlain by 9.1 m of low marls and shales typical of the Abarug (Alat) Marl.

ıe nearby Dam Formation measured type-section at Qarn Abu Wayil, unfortunately can lu - only the top of the Simsima Member outcrop.

ru (Alat) Dolomitic Limestone and Marl Member

Th s member is known as the Alat in Saudi Arabia where it is an important aquifer for the purposes of this study, the name Alat has been retained in reference to the ı-v stern part of Qatar.

The two units of this member are :- Abarug (Alat) Dolomitic Limestone:- A hard, brownish grey crystalline dolomite with numerous moulds and casts of fossils and up to 2 m thick, underlain by:- Abarug (Alat) Marl, a softish, off-white to yellow clayey dolomitic chalky marl, generally 10 m thick. Highly reflective, especially from the dusty weathered surface, it is usually compact at depth and nodular. Outcrops are restricted to the syncline east of the main Dukhan structure and to localised remmants on the western flank other than in the southwest where it underlies the Dam Formation and forms the importat Alat aquifer with its supportive yellow marly aquiclude.

Previous authors consider the Abarug to have been of widespread deposition over the Simsima Dolomite and to have been removed by subsequent erosion. However in many outliers, the Lower Dam Formation is found to rest directly upon Simsima Formation, with the Abarug absent. Thus in the Bayd el Q'a depression, where considerable core drilling has been carried out in the course of groundwater exploration, up to 10 m of white to grey chalky limestones of the Dam Formation are found to overlie the typical crystalline dolomitic limestone of the Simsima.

In boreholes P32 and P33 the Abarug Limestone (the aquifer) is up to 10 m thick while at Bir Zigrit only 2 m. This may be due to non-deposition or, more likely, pre Dam Formation erosion. The Abarug Member does not appear as a surface outcrop, emerging from beneath the Dam Formation, east of Abu Samra. Though it may be beneath some extensive areas of aeolian sand cover it is more likely that it wedges out complete subsurface and it has been shown thus on Enclosure 2. Therefore it is likely that the Abarug deposition was restricted, marking the gradual Upper Eocene emergence of Qatar, which lasted through the Oligocene until Lower or Middle Miocene times, when resubmergence lead to the beginning of Dam Formation deposition.

3.2.3.5 The Oligocene Hiatus

That the main process of dolomitisation of the exposed rocks of Qatar took place principally during the Oligocene is evidenced by the presence of dolomitised Simsima beds beneath only partially altered Dam rocks. The Abarug Member, although of restricted deposition, was also dolomitised at this time. Clear evidence of the chronology and the spatial relationship of these processes is derived from :

- the northern Abarug outcrops near Zikrit where dolomitised Abarug overlies unaltered Simsima, whereas in the absence of the Abarug, as is generally the case, it is the Simsima Member that is dolomitised.

- drilling results in the south west revealing undolomitised chalky limestones and marls, assigned to the Simsima Member, overlain by the protective Abarug (Alat) Member.

Further protection from subsequent diagenesis has been afforded by the Dam Formation marls and limestones deposited in Miocene times following the Oligocene Hiatus.

3.2. 4 Neogene Deposits

Following the deposition of the Dammam Formation wide-spread emergence occurred and considerable erosion took place. Marine conditions and deposition were re-established during the Miocene, although, in Qatar, the earlier strata found in adjacent parts of Saudi Arabia (i.e. Hadrukh Formation), are absent. The Neogene succession commenced in the peninsular area with the deposition of limestones and shales of the Dam Formation and eventually gravels, sands and conglomerates of the Hofuf Formation. Neither of these formations are of hydrogeological significance in Qatar.

4.1 The Dam Formation - Lower to Upper Miocene

The Dam Formation, which reaches a maximum thickness of about 80 m in Qatar, and is present only in the south central and extreme south-west of the peninsula, is divided into lower and upper members. The full thickness of the formation is only preserved when it is overlain by the Hofuf Formation. Type Sections selected by Cavalier (1970), from near Abu Samrah are presented as Figs. 3.16 and 3.17.

Lower Dam Formation

Up to 30 m of strata assigned to this division, are fossiliferous limestones, with considerable marl and clay, of marine origin. Two distinct clay beds each 4 to 5 m thick one red the other green can be traced over large areas of the south-west but the deposits thin eastwards and change to white marly limestone.

Upper Dam Formation

Marine conditions persisted in the south west and up to 50 m of alternating thin beds of marl, chalk and limestone were deposited which by erosion give a distinctive step and terrace appearance to the hills. Overall the very varied lithology of the Dam Formation, with rapid changes both vertically and horizontally, indicates a spreading lagoonal environment under near-shore conditions and the abundant fossils support this interpretation. It is difficult to separate the Upper from the Lower Dam in borehole cutting though a surface outcrop distinction can generally be made. However, sufficient of the Dam Formation deoposits survive in the south of Qatar and as far east as the centre of the country to support the supposition that they were once much more widespread and may have covered the whole of the peninsula area. The Dam deposits generally have a much less weathered appearance when compared to the underlying Eocene, again supporting the principle of the importance of the Oligocene period of diagenesis and erosion.

.2 Hofuf Formation - Miocene - Pliocene

With the final emergence of the Qatar peninsular, towards the end of the Miocene, deposition of widespread and consistent strata ceased. The onset of wetter conditions, associated with the developing polar ice caps and the southerly shift of climatic belts, resulted in the erosion and transport of coarse continental outwash material from the Saudi Arabian Shield area. Large river systems, which may still be traced by the presence of erosion valleys and related deposits of sand and gravel, brought sub-angular to well rounded pebbles of quartz, igneous rocks such as granite, porphyry and basalt, and the more resistant limestones, sandstones and conglomerates to be strewn as thin and irregular sheets across the Qatar land surface. The remnants of these deposite survive as isolated capping to the flat-topped (mesa) hills of southern Qatar where they seldom exceed 10 m in thickness.

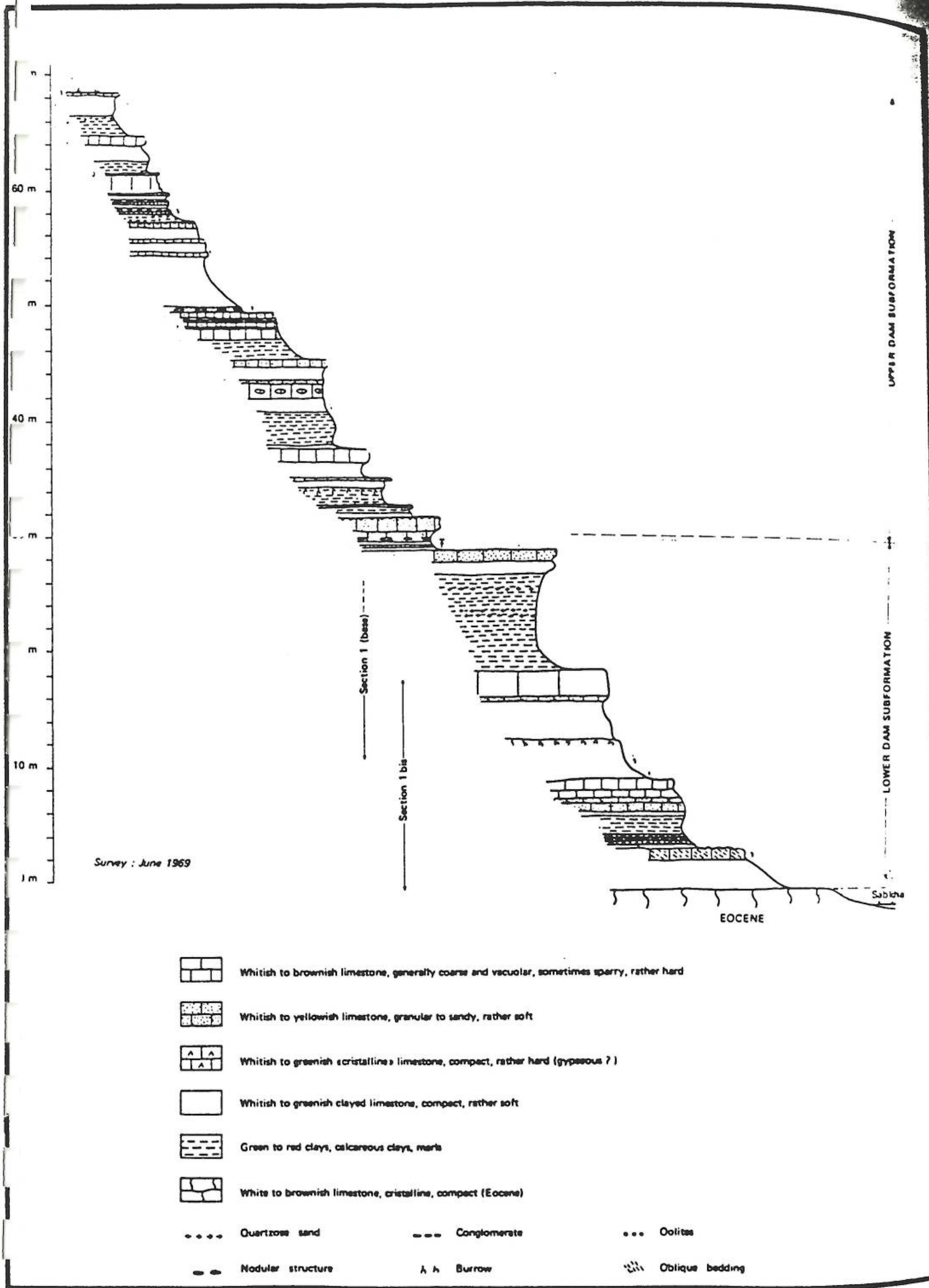
The Mukeinis depression in central Qatar contains an area of infilling of such gravel and sand providing valuable evidence on both the original extent of the gravel fans and the age and history of the formation of collapse structures.

3 Superficial Deposits Pliocene - Holocene

each Deposits

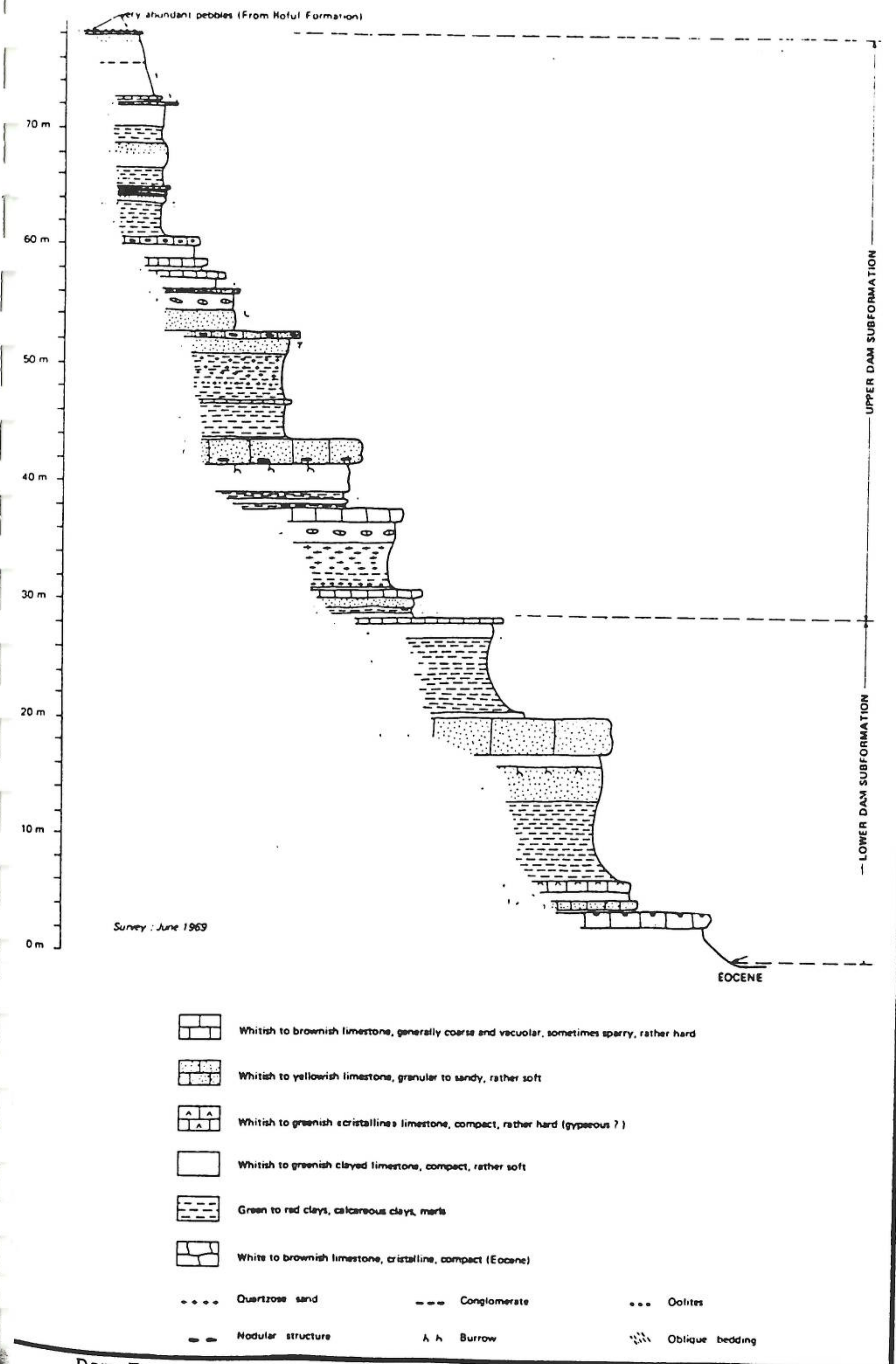
Coastal shallower water and continental deposits of a thin, intermittent and superficial xtent cover a large area of coastal Qatar. Cavalier (1970) records a number of conglomeratic beach gravels and calcareous sand deposits on marine terraces around the coast which are related to sea-levels up to 20 m above that of today.

Shell material from these raised beaches has been dated by ^{14}C methods (Vita - Finzi, 1978) as follows :



Dam Formation Type Section
Southern Flank of Qarn Abu Wayil
(after Cavalier, 1970)

Fig. 3.16



Dam Formation Type Section
Eastern Flank of Hazm Mishabiyya
(after Cavalier, 1970)

Fig. 3.17

Table 3.6

Radiocarbon Ages for Beach Deposits
Qatar

Site	Qatar Elev.	Age (Yr. B.P.)
Sharjah	6.00	> 35,000
South of Dukhan	5.00	21,950 ± 550
Dukhan	5.00	27,100 ± 900
Al Wakrah	4.50	> 35,000
Abarug	4.00	> 35,000
Wusail	2.00	5,830 ± 70
Khor	1.70	4,690 ± 80
Abarug	1.50	5,370 ± 80

All dates corrected for $\delta^{13}C$.

Although it is a commonly held view that global sea level did not rise above -50 m between 70,000 and 15,000 b.p. (before present), (Shackleton and Opdyke, 1973) others maintain that the sea lay close to its present level about 30,000 b.p. (Milliman and Emery, 1968). This latter view is supported by evidence from marine deposits in the Gulf at about this time. Fossil beaches at 4 and 5 m on Halul Island have yielded ^{14}C dates between 32,700 and over 44,300 b.p. and on Bahrain evidence of a 5 m raised beach has been documented (Brunsden et al, 1979). The three lower strand deposits lying between 1.5 and 2 m above high water give ages of between 4,700 and 5,800 years b.p. Taylor and Illing (1969) have reported three strand deposits in western Qatar lying between 1.5 and 2.5 m above sea level and dated by ^{14}C at 3,930 ± 130, 4,200 ± 200 and 4,340 ± 180 years b.p. respectively.

In Abu Dhabi, Evans et al (1969) obtained a date of 4,000 ± 200 years b.p. on certhid gastropods from the surface of a beach ridge 1.9 m above high water. Shell remains on a 2.0 m beach at Bahrain have been dated at 4,900 ± 150, 4,470 ± 110 and 3,130 ± 180 and similar remains on a 4.5 m beach between 6,330 and 6,920 b.p. (Brunsden, et al 1979).

Vita-Finzi (1978) has amassed considerable supporting evidence from neighbouring areas to propose that Qatar has been elevated by about 2 m in the last 5,000 years and this is believed to represent the continuation of a trend already manifested 20,000 y.a. The discrepancy between the ages and heights of raised beaches on Qatar and Bahrain may therefore possibly be explained through differential rates of eustatic rise.

Inland Gravel Deposits

Reworked gravels of continental origin occur at the base of mesas over limited areas in the south of the country. The composition of these deposits indicates that they have been derived from the Hofuf Formation by recent erosion.

Sabkha Deposits

In Qatar a land area of 700 km^2 is occupied by sabkhas, an Arabic term for inland or coastal saline flats or playas composed of fine silts and calcareous sands and these are widespread along the coastal margins of Qatar. They reach their most extensive development along the eastern coast to the south of Umm Said. The coastal sabkhas are generally above the present tidal range but represent Holocene sea inundations.

Away from the coast two extensive sabkha areas occur. In the south along the Saudi Ar ian border a major sabkha extends from the Gulf of Salwa south-eastwards. Of more hydrogeological importance to Qatar, however, is the extensive sabkha located to the east of Dukhan and referred to as the 'Dukhan sabkha'. The lowest point on the sabkha is -6 m be w mean sea level. Although much of this inland sabkha's deposits occur in the area of Depositional Sulphate Facies of the Rus Formation, they do cross the boundary to the Dukhan Depositional Carbonate Facies for some 15 km along the western margin.

Aeolian Sand Deposits

An irregular distribution of superficial aeolian sands is a featured of the Qatar peninsula. These occur in the form of mobile thin sheets, small hummock dunes, barchan dunes and large akle' type dunefields. The prevailing wind in Qatar is from the north-west (shamal) and the aeolian sands are thus heavily concentrated in the south-eastern corner of the country where numerous barchan dunes progressively coalesce into an extensive dune-field of the akle' type encroaching over coastal sabkhas.

The aeolian sands have originated from the limestone pavement of north Qatar, the coastal beach deposits in the north-western and the area between Qatar and Bahrain, now submerged by the sea. Wind ablation of the surface rocks has admixed calcareous and siliceous material in alm t equal proportions. In sheltered locations in collapse depressions, the sands intercept storm run-off water and often support a considerable growth of desert vegetation.

3.3 STRUCTURE AND EVOLUTION OF THE PENINSULA

3.3.1 Introduction

Although Qatar is located within the relatively stable geological area of the Arabian Interior Platform, its close proximity to the Gulf geosyncline to the northeast has subjected the peninsula to gentle tectonic activity which has persisted over a considerable period of geological time. The type of movement that has occurred has not resulted in major structural dislocation, but has produced important folding and significantly affected sedimentation. During the several periods of relative uplift and sea level adjustment during the Tertiary Period, inter-formational erosion, epignesis and karstification have had a significant impact upon many of the shallower strata and have greatly influenced the hydrogeological evolution of the peninsula.

3.3.2 Regional Movements

Gentle tilting to the north east has affected the Arabian Interior Platform area since the Permian in response to the complementary factors of subsidence and major sedimentation in the Gulf geosyncline. These movements have created a regional homocline extending from central Saudi Arabia with very gentle dips to the east and north east. In Qatar the effects of this regional tilting are masked by adjustments to local forces.

3.3.3 Regional Folding

The more prominent folds in Saudi Arabia and along the western Gulf are shown on Fig. 3.18. The gentle elongated periclines, which in many places form important oil-bearing structures, are considered to have a halokinetic origin i.e. are movements created by the re-distribution, at depth, of salt which flows by plastic deformation in response to isostatic stress. Deep seated faults are believed to have facilitated displacements and promoted salt migration and the formation of diapiric structures. Contemporaneous upward bulging of the positive or anticlinal areas has affected most of the Tertiary sequence sedimentation and may have affected even older formations.

3.4 FOLDING IN QATAR

The subdued surface relief and the general shape of the Qatar peninsular reflect the basic underlying geological structure which is of a gentle unfaulted form. Fig. 3.19. indicates the location of the principal named folds.

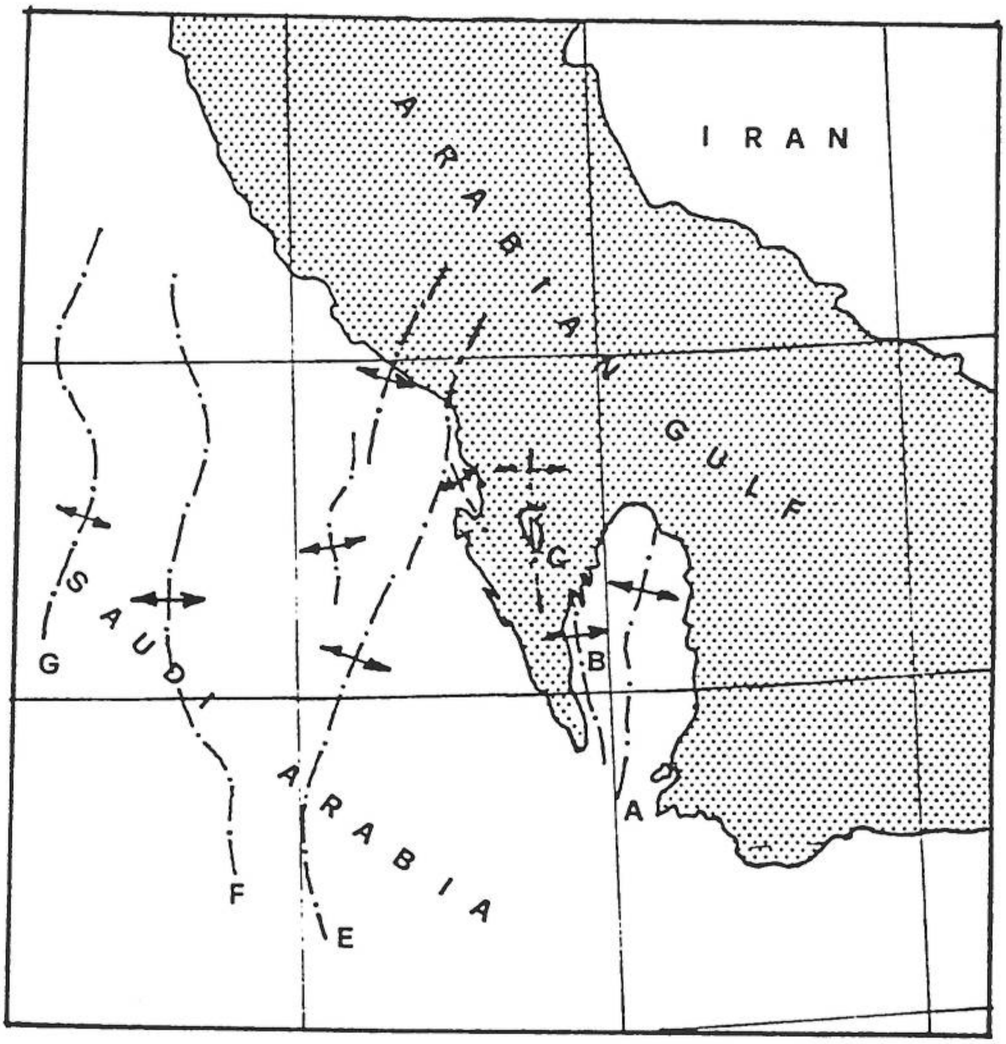
The principal structures converge in the southern border area of Qatar but subsurface structural information is limited. It appears that the positive areas do not continue into Saudi Arabia and gentle southerly pitching is therefore implied.

- Qatar Central Pericline

  A broad gently dipping arch, or pericline, forms the backbone of the mainland, the Qatar Central Pericline, and this culminates in the south central area with shallow pitching both northwards and southwards. In the north a - Y - branching separates the shallow Simsima Arch which also pitches though gently northeastwards.

- Dukhan Anticline

  The Dukhan Anticline in the west is a more pronounced structure creating a topographic ridge and erosion features, and it culminates some 40 m above the Central Pericline. Dips are also steeper and while the crest elevation is relatively constant the eventual northward pitch is also steep.



A : Qatar Pericline

B : Dukhan Anticline

C : Bahrain Pericline

D : Dammam Dome

E : Ghawar Anticline

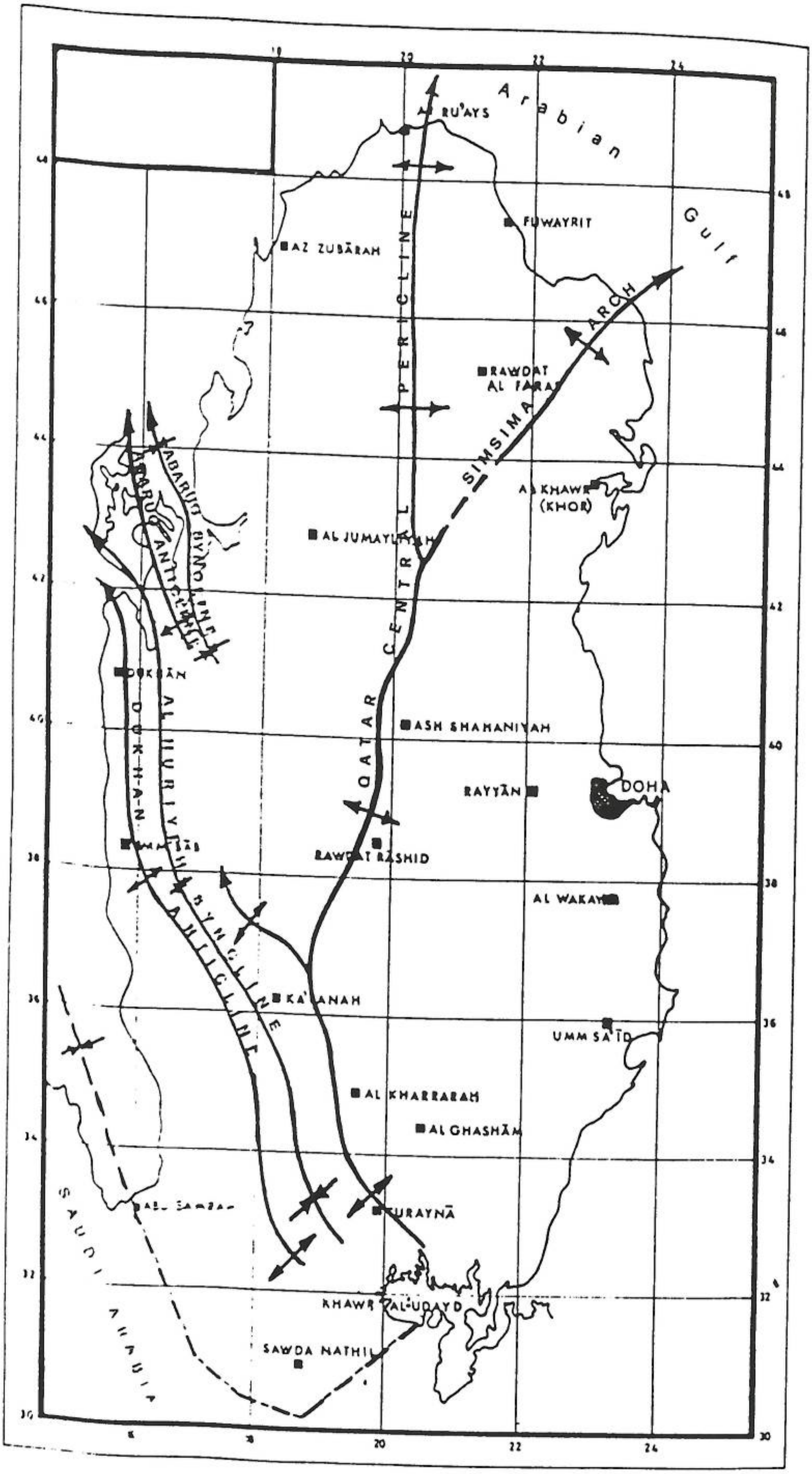
F : Khurais Anticline

G : Ma'aqala Anticline

AXES OF MAJOR ANTICLINAL STRUCTURES EASTERN ARABIA

(After Italconsult, 1969)

Fig. 3.18



PRINCIPAL GEOLOGICAL STRUCTURES - QATAR

Fig. 3.19

Hurijeh Syncline

The adjacent syncline has a steep westerly and a very gentle easterly limb and several minor folds and flexures are to be found within the area which separates the two main anticlines.

Salwa Gulf Syncline

This fold is known to have a gentle westerly limb in Saudi Arabia and is therefore a complement of the Hurijeh syncline. The shallow Gulf occupies the synclinal area and the artesian feature of the Alat (Abarug) Member of the Upper Dammam Formation in the Salwa area is created by the confined conditions and the relative elevations of the two limbs.

Abarug Folds

A complementary minor synform and antiform structure creates the peninsular of Abarug on which a thin capping dolomite, overlying a thicker dolomitic chalky marl, (Abarug Members of the Upper Dammam Formation) are preserved as outliers resting upon the general Simsima Formation surface.

.5 STRUCTURE CONTOUR MAPS

Sufficient stratigraphic and structural data are available from the records of pl :atory, development and production drilling to permit the preparation of structure ntour maps. The horizons selected are the top of the Umm er Radhuma Formation and the p of the Lower Dammam Formation.

The marked change in lithology from a softer, pale marly, chalky and frequently psiferous, dolomitic limestone to a harder, grey-brown, vesicular dolomite has facilitated e cognition of the top of the Umm er Radhuma Formation, in cuttings from boreholes of equate depth, and the configuration of this surface is presented as Fig. 3.20.

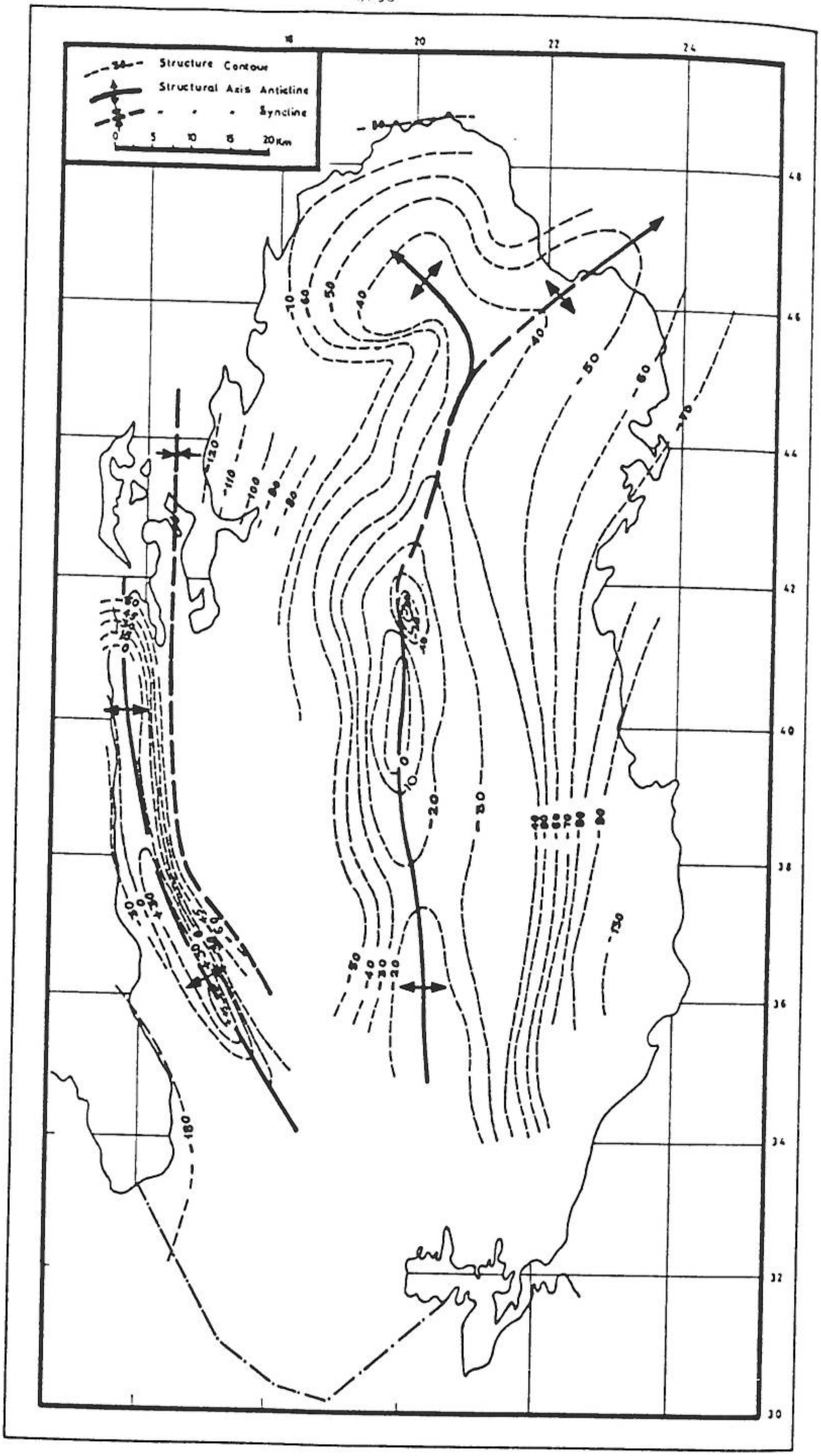
he easily recognised diagnostic fossil foraminiferan, Alveoline elliptica, of the ha Alveolina Limestone Member of the Lower Dammam Formation, has provided a valuable relation horizon within the Middle Eocene; the oil exploration E_1 marker. The attitude th s stratigraphical higher horizon is presented as Fig. 3.21, based largely upon the ul s of Q.P.C. exploration.

ps of the Umm er Radhuma Formation are generally very low, less than 0.25° (1:250 +) in to a maximum of 1.5° (1:40) on the flanks of the Dukhan anticline only through eper than average are apparent on the eastern limb of the Central Pericline. Even ll er dips are found at the Alveolina horizon. This is explained by the variation in k ss of the Rus Formation being thin over the positive areas and thickening both east west towards the margins of the peninsula and beyond.

th the accepted structural control of the depositional conditions and therefore the ent-day formational facies, the following suppositions may be made;

t stability of the main positive areas of the Central Pericline and the Dukhan A.cicline are noteworthy.

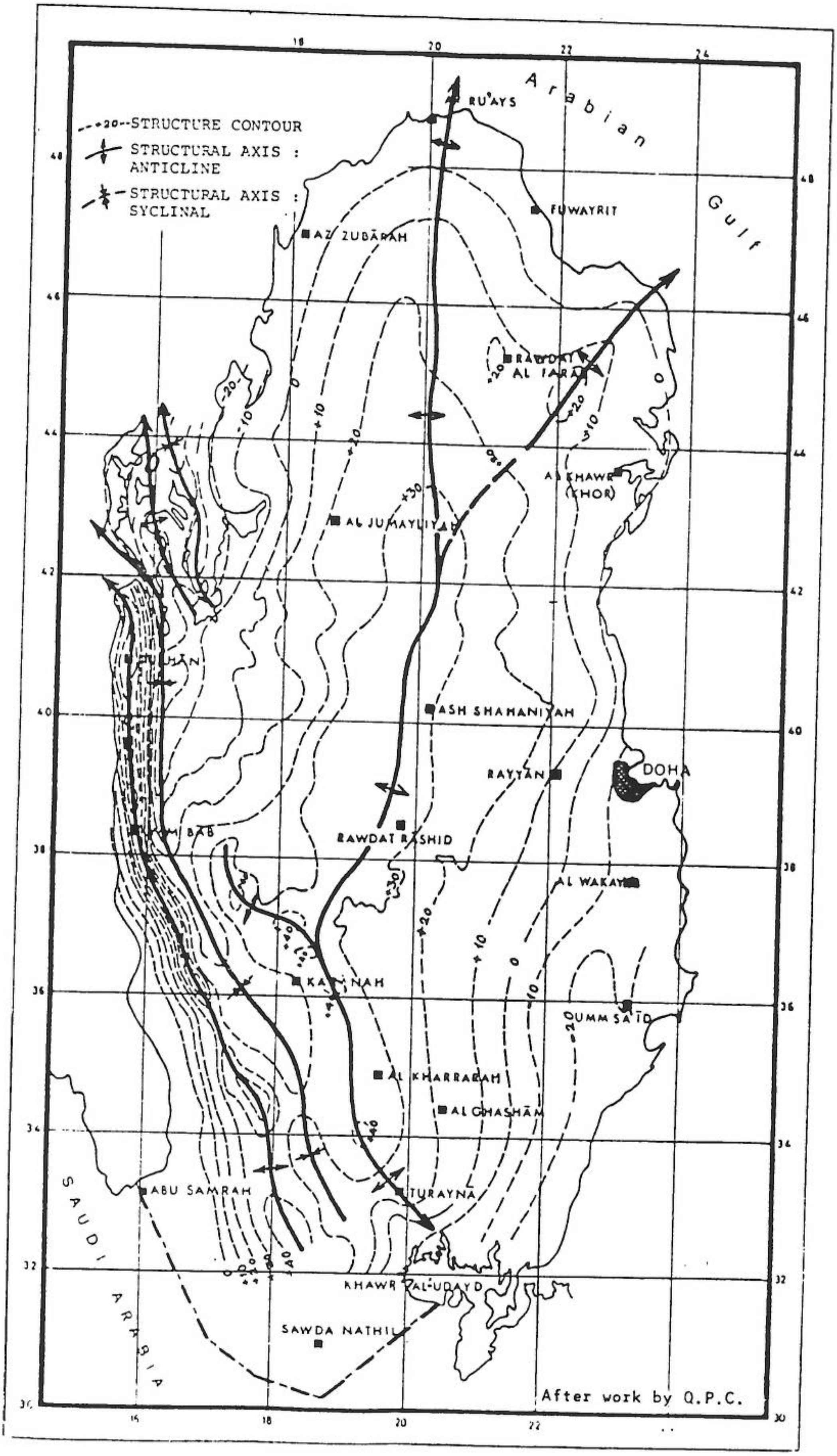
t northern extensions of the Pericline change however with a general clockwise r ation between top Umm er Radhuma and top Lower Dammam times. This rotation is regarded as the origin of the northward enlargement of the area of Rus Formation D ositional Carbonate Facies accumulation and consequently the generally V-shaped c figuration of this and other facies of the Rus. More detailed information on formations both older and younger than the Rus may reveal a much longer period of fa es control by structure.



STRUCTURE CONTOUR MAP

Top of Umm er Radhuma Formation

FIG 3·20



STRUCTURE CONTOUR MAP

Fig. 3.21

Top of Dukhan Alveolina Limestone Member of the Lower Dammam Formation

3.6 EUSTATIC AND RELATED PALAEO-CLIMATIC EFFECTS

Karstification and erosion related to isostatic and eustatic events, palaeo-climatic and palaeo-groundwater conditions have had significant post-depositional effects upon the strata in Qatar.

Palaeo-karstification is an important feature of much of the Umm er Radhuma Formation. Lost circulation reported in oil exploratory and in Project drilling testifies to its presence at a number of horizons below the top of the unit. Active karstification is unlikely to be a feature of the present groundwater flow, which trends to saturation with respect to calcite and dolomite away from the area of low salinity groundwater storage in the north centre of the peninsula and must be therefore be a feature of a palaeo-system. Emergence of positive areas may have occurred as a part of a general uplift which started at the end of Umm er Radhuma times and continued until the Lower Dammam transgression and kartsification of such areas at that time is a possibility. Further karstification may have occurred during the upper Eocene and Oligocene hiatus and following the final emergence of the peninsula in Upper Miocene times.

The widespread occurrence of collapse depressions over the peninsula (Section 3.2.3.2) is related to karstification of the Rus Formation. Gypsum dissolution by circulating groundwater has created extensive cavity formation in the Rus Formation, collapse of remnant material and a general thinning of the unit in such areas. This process has been widespread in the western Gulf and Figure 3.10 indicates the relationship of the two principal Rus facies and the extensive area where gypsum solution has influenced groundwater conditions.

Gypsum dissolution is occurring at present as a feature of groundwater flow and it is probable that the karstification has been a continual process since the main emergence of Rus Formation areas above sea level.

The mechanics of the solution process are illustrated in Fig. 3.11 and the major cavern of Dahl el Misfir and the smaller ones at el Mudlham and el Hammam provide field evidence. Few caves and caverns are accessible now but it is certain that many more lie hidden by a thin roof cover or have suffered the subsequent collapse and infilling which is a feature of such erosional structures.

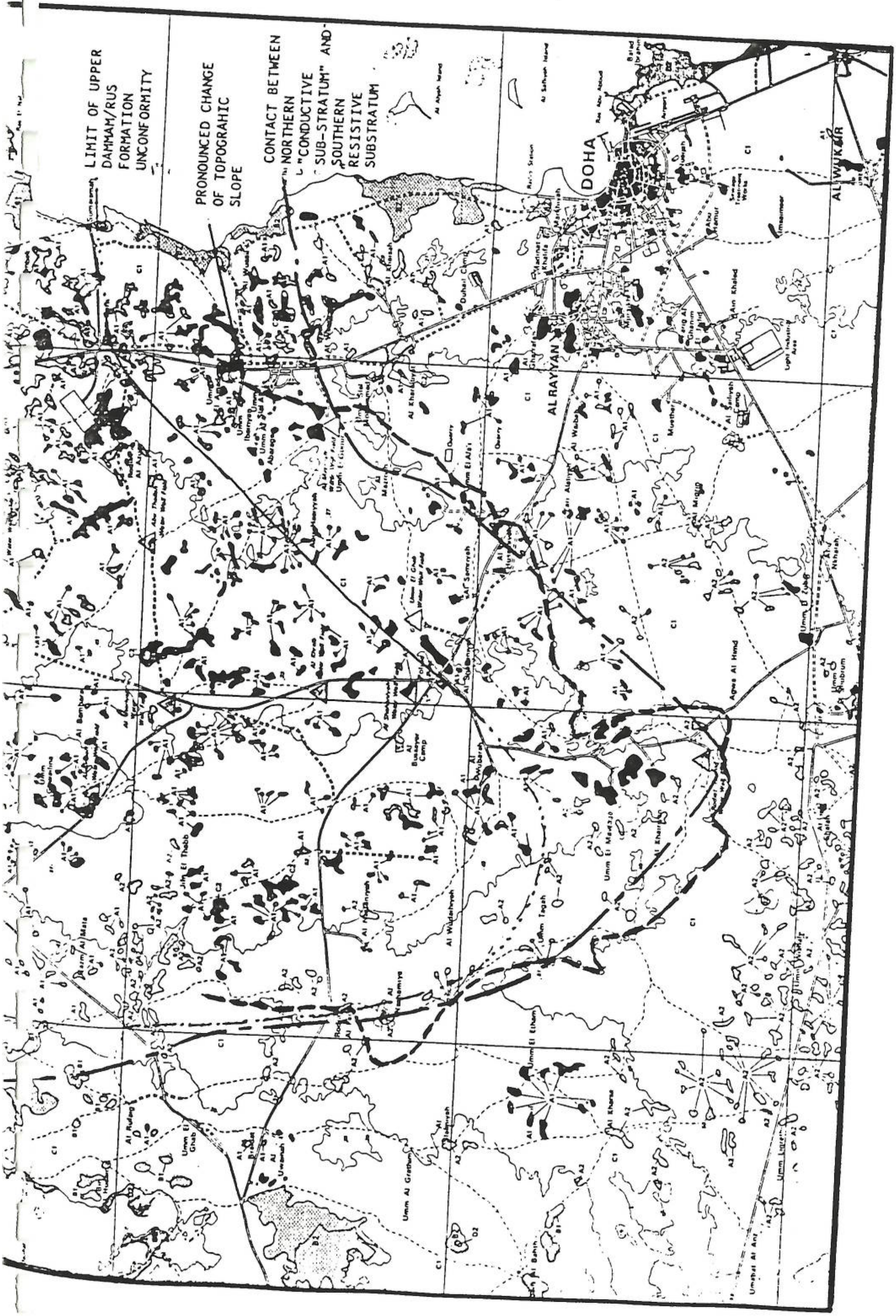
The overlying Dammam Formation at these localities remains relatively undisturbed and there is no evidence of post-solution sedimentary infilling into the Rus. It is concluded therefore that the karstification commenced in post-Miocene times (Cavalier, 1970) and continued during the Plio-Pleistocene up to present times. As Qatar was a land area during the Quaternary pluvials (Section 3.2.4 and) it is probable that much of the karstification occurred during these relatively recent periods. As is discussed later the presence of these collapse depressions has had a fundamental effect upon the present groundwater regime in Qatar.

Fig. 3.12 illustrates the similarities and differences between collapse structure in two differing facies of the Rus. It is in the rim areas of the Southern Sulphate Facies type that caves and caverns may be expected and they are regarded as a feature of the active and continuing gradual expansion of the collapse structures due to the marginal solution and removal of gypsum.

Evidence of the linear collapse illustrated in Fig. 3.11 is clear at Umm Taqah and near Rawdat Rashid.

That the absence of Lower Dammam shales has faciliated the rainfall recharge to groundwater and the consequent removal of soluble anhydrite is clearly shown by the concurrence of the boundary between the area where shales are present to the south and their absence to the north. (Fig. 3.22).

S LUTION SCARP AND RELATIONSHIP TO GEOPHYSICAL AND STRATIGRAPHIC EVIDENCE



"Undercutting" or a migration of the solution front southwards beyond the "shales boundary" has taken place in the south and southeast of the belt.

South of this solution front recharge has penetrated the Dammam Formation to remove the anhydrite in the collapsed areas, via enlarged joints and fractures which also effect the relatively incompetent shales below.

ERTS/LANDSAT imagery of Qatar reveals numerous NNW-SSE linear trends in the north of the peninsula which are related to the transport of aeolian deposits by the prevailing winds.

Curvilinear and sinuous trends are also visible and these are found to consist of smooth extensive cherty limestone pavements, semi-parallel and at intervals in the generally non-linear desert surface. They are regarded as strand lines and erosional benches, possibly of considerable age, which are being re-exposed by present-day erosion.

IV

SOILS AND VEGETATION

4.1 SOILS

The most widespread soils of Qatar are very shallow (10-30 cm) calcareous sandy loams covered with rock debris and overlying a layer of rock fragments on limestone bedrock. These lithosols are of little to no agricultural importance. However, in approximately 850 separate depressions throughout the country colluvial soils made up of calcareous loam and sandy clay loams have accumulated to depths ranging from 30 cm to 150 cm overlying limestone debris and bedrock. These colluvial deposits are generally of limited areal extent and separated by the lithosols of higher ground and may range in extent from a few hectares to a maximum of 60 ha with a total aggregate extent of 29,620 ha. These depression soils are generally known as rodha (pl. rodat or riyad and constitute the main agricultural soils of the country and are the focii of ponded run-off and subsequent recharge. Elsewhere, particularly in southern Qatar, aeolian sands have accumulated and along the coastal margins, saline soils (sabkha) occur in extensive playas of a total aggregate area of 66,000 ha.

A reconnaissance soil survey of Qatar was completed in 1973 (FAO Technical Report 1, QAT/71/501), and recent investigations have been directed towards detailed soil surveys and soil management studies. The original soil survey classified the soils of Qatar into four soil associations and eight soil series, summarized as follows :

Rodha Soil Association (A)

Series A1 : Silty clay loam to clay loam sometimes with soft lime segregations of a moderately deep profile (23,100 ha.).

Series A2 : Sandy loam to sandy clay loams with a shallow to moderately deep profile with a surface cover of aeolian sand 10 to 15 cm deep occurring in hummocks around vegetation (4,520 ha).

Saline Sabkha Soil Association (B)

Series B1 : Gypsiferous depression soils of clay loam texture and greyish clay in the sub-soil as a result of water logging (6,517 ha).

Series B2 : Sandy clay loam to sandy loam in texture with profile depth of 40 to 100 cm. Characteristic sabkha deposits of southern Qatar (63,607 ha).

Lithosol Association (C)

Series C1 : Very shallow soils (19-30 cm) of calcareous sandy loam uniformly covered with rock fragments scattered on the surface and overlying a layer of rock debris, followed by limestone outcrop (958,072 ha).

Series C2 : Rocky hill outcrops, mainly in central and southern Qatar (62,925 ha).

Sand Soils Association (D)

Series D1 : Aeolian sandy soils of southern Qatar characterized by a deep profile with calcareous coarse sand to loamy coarse sand and an admixture of desert and marine sand. Occurring either as a thin mantle overlying rodha soils or bare rock in depressions, or is isolated mobile barchan type dunes on a limestone pavement (4,775 ha).

Series D2 : While oolitic sand of marine origin, usually found adjacent to the coast (31,392 ha).

Table 4.1

SOIL CHARACTERISTICS AT BARADA, NORTH QATAR

(PHYSICAL AND CHEMICAL)

Characteristic	Depth, cm		Soluble cations and anions me/L	Depth, cm	
	0 - 15	30 - 45		0 - 15	30 - 45
Clay, %	42	42	Ca	35.7	34.4
Silt, %	25	26	Mg	20.5	13.7
Sand, %	33	32	Na	66.0	59.9
Texture	Clay	Clay	K	3.22	2.24
Field capacity, %	24	25	HCO_3	1.38	1.23
Wilting point, %	15	15	Cl	57.7	64.0
Available moisture, %	9	10	SO_4	66.4	51.2
Moisture saturation, %	56	58	Exchangeable cations, me%		
pH	7.82	7.80			
EC x 10^3	9.83	9.56	Ca	10.8	10.9
$CaCO_3$, %	17.8	19.5	Mg	4.36	4.20
Organic matter, %	0.49	0.27	Na	4.21	3.81
P, ppm	15.5	13.7	K	0.79	0.77
N, %	0.05	0.04	CEC	19.3	18.3

The analysis is the mean of the 136 and samples collected from Blocks 6 and 7 at the farm.
Clay = <0.002 mm; Silt = .05 - 0.002 mm; Sand = 0.05 - 2 mm.

Table 4.2

DETAILED SOIL PHYSICAL AND CHEMICAL ANALYSIS

OF CALCAREOUS SOILS OF NORTHERN QATAR

Characteristic	Barada	Poultry Farm	Rodiat el Faras
Size. fractions, microns %			
5000 - 2000	0	0	0.1
2000 - 600	1(<0.5)	3(<0.5)	1(<0.1)
600 - 212	3(1)	3(1)	4(3)
212 - 63	6(4)	8(7)	11(9)
63 - 2	52(51)	48(59)	48(46)
2	38(44)	39(33)	36(42)
CEC (2 mm soil), me	26.5	31.9	25.0
CEC, separated clay, me	45.6	52.2	51.0
Organic carbon, %	0.91	0.69	0.72
$CaMgCO_3$: $CaCO_e$ ratio	1:3	1:9	1:3
Free Fe Oxides, %	1.42	1.51	1.43
Total Fe, %	3.51	3.57	3.31
Zn, ppm	112	99	112
Mn, ppm	511	547	521
Cu, ppm	< 0.2	< 0.2	< 0.2
Mo, ppm	<0.5	< 0.5	< 0.5

The practice-size fractions are on the dried at 105°C and organic free basis. The value in brackets are on CO_3 - free basis. Separated clay (organic matter and CO_3 removed). Organic carbon (< 2 mm soil, 105°C basis). CEC is expressed in me/100 g.

Subsequent detailed soil surveys undertaken by the Project have retained this classifi-at n, but additional detailed soil surveys of specific areas of Qatar undertaken by consult-nt to the Industrial Development Technical Centre (IDTC) are based on the soil texonomic lassification of the 1965 National Co-operative Soil Survey of the United States. This l sification has recognized nineteen series of three orders (entisols, aridisols and en .sols) and provides a valuable basis for further work in soil classification in Qatar. Metcalf and Eddy, 1977).

The physical and chemical characteristics of the northern calcareous soils are described n detail in Project Technical Report No. 2 (Soil Management) and only a summary is given ar The surface layer is compact and cracked and water infiltration rates vary from 2 to c /d in the saturated and dry condition respectively. The proportion of clay (42%) and silt 16%) remains relatively constant up to 45 cm depth and structure is under-developed with a en ency to form sub-angular blocks. Field moisture capacity and available moisture are low e compared to similar textured soils elsewhere. Owing to their calcareous nature ($CaCO_3$ % and lack of organic matter (0.4%), a hard surface crust or hard-pan is often formed which n bits infiltration and interferes with the emergence of seedlings and creates unfavourable a -air-water relationships. There is a deficiency of major nutrients and some trace ements. Sodium and magnesium tend to dominate in the soil solution while chloride and lphate are the major balancing anions with potassium and bicarbonate present in small a ities. Exchangeable calcium is the dominant cation and exchangeable soidium is high.

Three samples of calcareous soil (roda), (one from virgin calcareous soil at Umm Garn u ry farm) were subjected to detailed physical, chemical and mineralogical analysis at the i ersity of Birmingham, England, the results of which are shown in Table 4.2 In calcium rbonate free soil, the clay content is increased by about 16% but other fractions show only i t variation. Cation exchange capacity of the separated clay, free from organic matter d arbonates, is 50 meq/100 g. The soils contain both dolomite and calcite forms, their erage ratio being 1:3 and 1:9 in the cultivated and virgin soils respectively. The clay a ion, determined by X-ray refraction shows poorly crystallised geothite (1.45% free ion i s) in two forms, one as roughly spherical bodies and secondly, unevenly distributed atings on the clay flakes. Also present are the minerals of illite (40%); magnesium l te (20%); tabular hydrated halloysite (20%); randomly interestratified illite smectite 0% and koalinite (10%).

The second series of soils of importance, as yet only experimentally cultivated and e ped, are the considerable areas of sandy soils (series D1 and D2) of southern Qatar of total area of 36,167 ha. In south-western Qatar the project established a pilot farm on e D2 series of these soils in 1978 and where a programme of soil management, agronomic and ri tion trials were undertaken. These aeolian sands often overlie saline sabkha and broken rine shells with gypsum are common on the surface. Organic matter is almost entirely absent as a result field capacity (2%) and available moisture (1%) are both extremely low. The r e of five soil profiles at this site show a calcium carbonate content of 3%, a pH of d a progressively increasing electrical conductivity with depth, from 6.0 mmhos at 0 cm to 12.5 mmhos at 1 meter. Sulphate and chloride are the dominant anions (42 and 39 L n the saturation extract respectively) in the surface layer and steadily increase to a t of 240 cm. Sodium, calcium and magnesium are the major cations where they attain levels 29, 36 and 15 me/L in the surface layer. Sodium adsorption ratio values increase steadily h epth; 5.64 at 0-30 cm, 14 at 1 m and 35 at 2 m.

Recharge to groundwater occurs either directly to both the widespread lithosols and bare c p surfaces after sustained rainfall or indirectly by run-off to the numerous depressions o hout the country. Observations of up to 30 run-off events (Table 6.1) have shown that igh but variable proportion of this run-off is subsequently infiltrated to the depression luvium soils and recharged to groundwater through the peripheral shallow coarser fraction l underlain by a fracture system associated with the collapsed structure. It is difficult assign average values of run-off and infiltration with any confidence (Chapter VI) owing the highly variable nature of rainfall amount, intensity, antecedent soil moisture and soil ra teristics. However, an examination of available data on soil depth, field capacity, k ensity and infiltration rates shows that ...

A2 series may be grouped into three main physical classes covering the northern and east central, west central and southern regions of the country.

Table 4.3

Physical Characteristics of Colluvium (Depression) Soil

Region	Area ha	Average Depth cm	Field Capacity %	Bulk Density gm/cm^3	Infiltration Rate m/d
North and East Central	19,811	80	26.8	1.4	0.18
West Central	6,176	60	14.5	1.5	0.36
South	6,273	60	5.0	1.8	1.08

The infiltration rates given in the above tale are those determined by a ring infiltrometer but subsequent run-off observations covering large areas of depression soils have shown that the true infiltration rate is much less, in the range 0.012 m/day to 0.0108 m/day.

4.2 VEGETATION

Natural plant growth in Qatar is limited by the seasonal erratic and variable rainfall and an aerial view of the peninsula will perhaps convince the observer that the country is entirely devoid of vegetation. Six types of plant community have however been recognised (Obied, 1975) and these repeat themselves wherever similar soil and water conditions occur. These community types are : (1) coastal sabkha (2) coastal sand (3) rodha depression (4) sand dune, (5) Acacia totillis and (6) Ziziphus nummularia. The plant communities of the sabkha and coastal sands are precominantely halophytes (Halopeplis perfoliata, Zygophyllum coccineum). The roda community type is confined to the colluvium depressions of the same name with mixed and pure stands of A. tortillis (samr), z. numularia, (sidr) and Lycium shawii (awasi) forming the permanent feature of the landscape and the most outstanding vegetational feature of Qatar. However there is considerable variation in floristic composition of these depression communities. Those of the northern half of the country have deep soils whereas one moves southward these have become partially infilled with aeolian sand and exhibit a different vegetational pattern. The density of vegetation is also greater in the depressions of the south where the sand has the effect of intercepting storm run-off and thus allowing a denser cover of Acacia-Ziziphus-Lycium association with Fagonia indica as the dominant ground species.

The natural vegetation of Qatar has for long provided limited browse grazing for camels and, particularly after good winter rains, for sheep and goats. Stocking at the present time is very low and there are no signs of serious overgrazing. This has undoubtedly been brought about by the changed socio-economic circumstances of Qatar where there are few, if any, people relying on nomadism as their sole support. These changed economic circumstances appear to be exerting a beneficial ecological effect on the landscape whereby areas of grass have been observed to remain ungrazed from one winter season to the next and thus adding, imperceptably at present, organic matter to the soil (Pike, 1979).

4.3 SOILS AND VEGETATION AND THEIR RELATION TO RECHARGE

As will be shown, there are two separate and distinct groundwater provinces in Qatar; a northern lens-type aquifer system developed in the carbonate facies of the Rus formation and a more complex system of minor sometimes perched and discrete freshwater lenses within the gypsiferous facies area of the same formation in western and southern Qatar. The distribution of vegetation in depressions appear to be closely correlated with these two groundwater provinces whereby the depressions of northern Qatar, and those coinciding with the freshwater en , are generally bare and contain only scanty vegetation. In contrast, the depressions of central and southern Qatar are generally well vegetated where sometimes moderately dense sar s of Acacia-Ziziphus-Lycium have become established on the aeolian sands overlying sandy oa soil (Series A2).

Field observations have shown the infiltration to roda soils and subsequent recharge s relatively direct process either after soil moisture is satisfied or around the margins f the depressions where there is a thin mantle of soil and where fracturing of underlying i stones is likely to attain a maximum. However, in west-central and southern Qatar the o r of aeolian sand would appear to intercept run-off to the depressions thus allowing a dense cover of vegetation to become established with little to no deep percolation beyond he underlying sandy loam colluvium. Further detailed soil moisture observations are required o ully substantiate this hypothesis but it is clear that the present stands of vegetation n southern Qatar must be sustained by intermittent run-off into the depression because the roundwater table may vary from 30 to 50 meters below ground level and therefore beyond the a e for root depth. Groundwater recharge is therefore likely to be considerably less in southern than in northern Qatar.

V

CLIMATOLOGY

5.1 INTRODUCTION

Climate is the major factor in water resources and agriculture in Qatar and a full under-standing of its limits and variations is an essential pre-requisits for future planning. A tailed analysis of the agro-climatology of Qatar was published in 1978 (Technical Note No. 1 S), Pike), but is now brought up to date by this report.

Air temperature, humidity, windspeed and rainfall have been observed by the Department Civil Aviation at Doha Airport since 1962 and at desalinisation works in Doha by the Water Department from 1958. An analysis of this pair of records has however shown considerable discre-pancies which cannot be entirely explained by the different exposures at the two sites. The a Airport records are considered to be the more accurate of the two and these are now the officially accepted record by the Meteorological Department. Other temperature and humidity records maintained by the oil companies are available from Dukhān, Umm Sa'id and Halul Island varying periods.

In 1972 a complete hydrometeorological station was established by the project at Rawdat-a Faras experimental station (Government Farm) in northern Qatar where records of temperature, humidity, solar radiation, windspeed, soil temperature, evaporation and rainfall have since been maintained. In October 1973 an additional hydrometeorological station was established at Decca (Abu Nakhlah), some 15 km WSW of Doha and in August 1975 a further station was es ablished at Abu Samrah on the south western coast to provide data for proposed agricultural development in that area (See Fig. V.I). Data from these stations have been processed, filed on the project computer system, analysed and published in Technical Note No. 6 (Hydrometeoro-lo cal Data Book 1972-79, Rogers and Youssef, 1980). A summary of these data are given in Appendix V.

5. ATMOSPHERIC CIRCULATION CHARACTERISTICS

Qatar lies wholly within the northern hemisphere desert belt. This belt experiences ve where some sporadic rainfall derived mainly from Mediterranean type depressions and from localized weather phenomenon known as a boundary front.

It appears, from the limited amount of synoptic data available, that Mediterranean type epressions occasionally retain sufficient energy for their associated cold fronts of polar o have an attentuated effect on the weather over Qatar, but in general the peninsula lies, nter, in a region of warm subsiding air associated with the winter position of the sub-opical Jet Stream (STJ). The STJ is a continuous hemispherical wind system just below the 0 mb surface at about 9,000 m and recent studies show that it is a steady powerful current ghout the winter. In general, the jet axis curves across North Africa, over southern bya to northern Jordan and western Iraq, from where it pursues course along the Arabian Gulf d then follows the Makran coast to reach India at about 22° latitude.

Precipitation during the winter appears to be closely connected with the position of the J. Where the velocity of the STJ decreases, as it does over the Arabian Gulf, kinetic energy verted into potential energy with a consequent increase in pressure. The decrease in ty is accompanied by vertical circulation with subsiding air, due to an increase in ssure, on the one side of the axis. The result is that warm air descends over the southern of the Gulf where as the north of the axis the air remains relatively cool. The possi-of widespread winter rainfall over Qatar is therefore very low because this upper air sidence inhibits convection and causes a blocking effect of Mediterranean type cold fronts eastward across northern Saudi Arabia and Iraq. Occasionally, however, these fronts do ite as far as Qatar but the effect is relatively minor and generally only small amounts rain of low intensity are likely to occur.

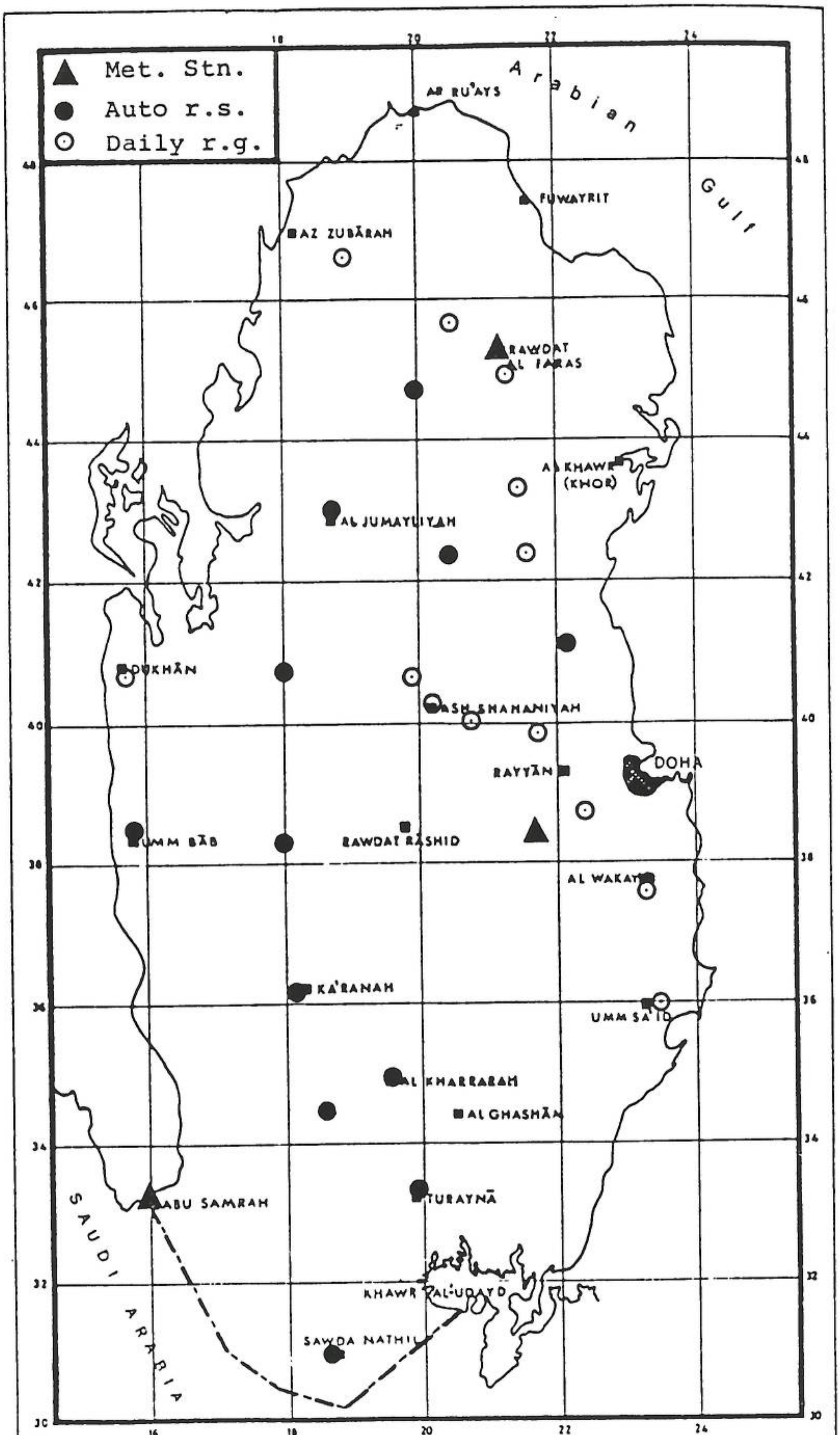


Fig. 5.1 Hydro-meteorological Network

The climate of Qatar is also however, affected by the Arabian Gulf, not only in terms of te erature and humidity, but also in the occurrence and distribution of rainfall. Notwith- stunding the inhibiting effect of the subsiding air, lower tropospheric boundary fronts are often found within the Gulf itself and this weather condition would appear to be the origin of ma rity of rainfall occurrences over the peninsula. Environmental isotope data would seem to onfirm that rainfall recorded at Bahrain is largely derived from the Arabian Gulf where the rapid evaporation at the sea surface inhibits full equilibrium conditions between the vapour ha e and the residual fluid. (For a fuller discussion see Chapter IX). Such frontal condi- id s are set up between two air masses with the marked characteristic that the front will form long a line parallel to the isobars, instead across them as is found in more northern latitudes. ha low warm air sometimes covers the Gulf and the Euphrates delta region with an anticlockwise in ulation around a low at the head of the Gulf, giving northwest winds over Qatar and a line f convergence or boundary front between this warm air and colder continental polar air lying ar lel to the main wind direction and the isobars. The intensity of rainfall along such a ro . will depend largely on the degree of temperature differential between the two air masses.

The reservoir of moist air at shallow levels in undoubtedly provided by the warm waters e Gulf. Sea temperature observed at Doha Harbour normally reach 35° during the summer nths, falling to 27° during the early winter months, which is 5°C above the mean air m rature at the time.

3 TEMPERATURE AND HUMIDITY

Despite the fact that Qatar is a relatively low-lying peninsula protruding into the abian Gulf, the temperature regime closely resembles that of inland sites of eastern Saudi ab a of a moderate continental type. The maritime effect of high humidity and a reduced ng in mean air temperature is confined to a narrow coastal belt. Within 10 km of the coast e average annual relative humidity has been observed to decrease by approximately 10% and e erage range of air temperature is increased by 2.5°C., with night-time minimum tempera- te uring the summer 3 to 4°C. lower than on the coast. The climate is further modified agricultural oases where the presence of vegetation and open water surfaces has the effect r ucing windspeeds, increasing the relative humidity and slightly lowering the air p ature.

ab e 5.1 presents mean monthly temperature data from four stations of Qatar from observa- n maintained since 1972.

Table 5.1

Mean Monthly Maximum and Minimum Temperature

(°C.)

ation	O	N	D	J	F	M	A	M	J	J	A	S	Ann.
Doha	35.7	29.7	24.4	22.0	23.2	27.5	31.3	38.3	41.2	41.5	40.8	38.6	32.8
R. aras	35.9	29.2	24.1	21.1	23.1	26.7	31.8	38.3	40.9	41.4	41.6	40.3	32.8
Decca	36.2	29.6	24.4	21.4	23.2	27.2	33.6	39.6	42.6	42.1	42.5	40.8	33.6
bu Samrah	34.0	27.5	23.8	21.6	22.7	25.9	32.0	36.0	36.8	38.1	38.3	38.3	31.1

n Minimum Temperature

	O	N	D	J	F	M	A	M	J	J	A	S	Ann.
oh	22.9	19.4	14.6	13.1	13.4	16.9	20.0	24.0	27.4	28.4	28.2	26.0	21.2
. ras	20.2	16.1	13.3	11.5	12.1	14.8	17.9	22.1	24.8	26.4	26.0	23.5	19.1
ecca	20.2	16.8	13.5	11.0	11.8	15.2	18.8	23.5	24.6	26.4	26.9	24.5	19.5
bu Samrah	21.1	17.0	14.0	11.7	12.2	15.6	19.7	23.6	25.6	27.5	26.9	24.5	20.0

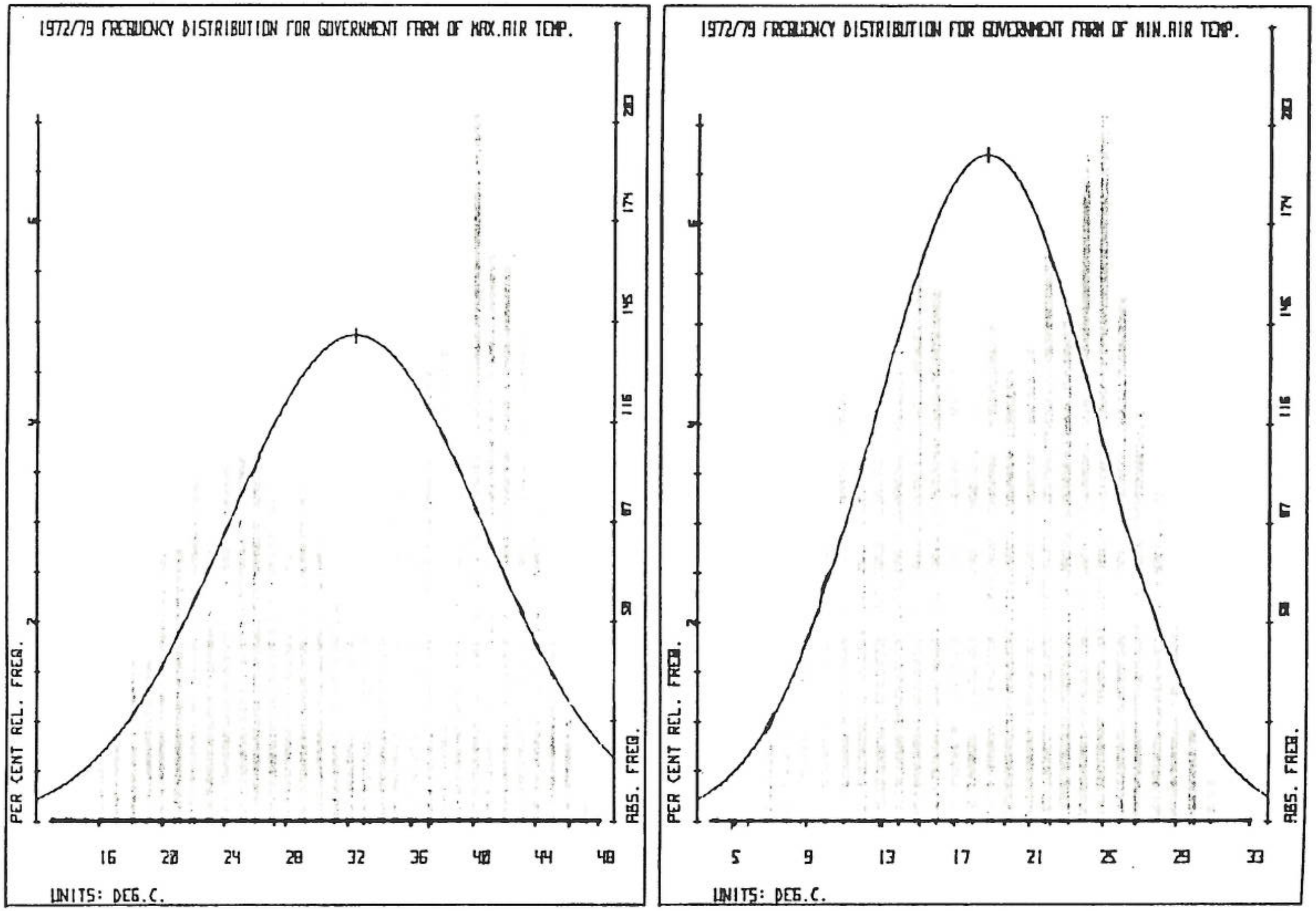


Fig. 5.2 Frequency distribution of maximum and minimum air temperature - Rawdat el Faras (Government Farm)

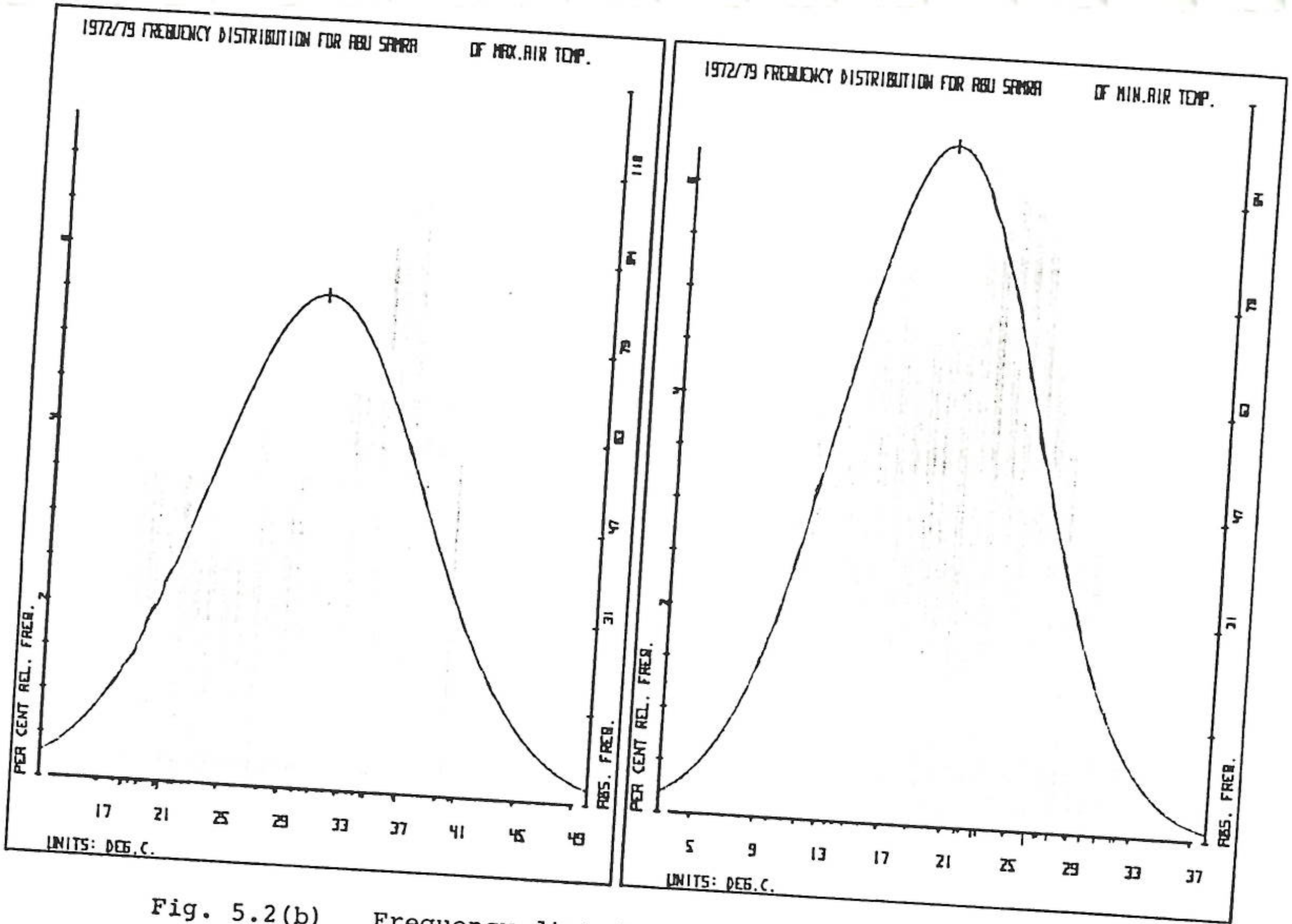


Fig. 5.2(b) Frequency distribution of maximum and minimum air temperature - Abu Samrah

Minimum temperatures are reached in January with a lowest recorded temperature of 3.8°C (Jan 1964, when -3.8°C was recorded at Abqaiq in Saudi Arabia). From mid-February onwards temperatures increase steadily, accelerating to maximum values of over 40°C during late April - early May. Maximum temperatures are reached in July or August with a highest recorded temperature of 49.0°C (1962). Of particular interest is the difference in temperature regime between the east and west coast of Qatar. Throughout the year both maximum and minimum temperatures of the west coast are 1-4°C lower than the east coast and this is brought about by the general cooling effect of the onshore north westerly wind along the west coast, whereas the east coast is subjected to advection from a warmer desert interior, particularly during the summer.

Of particular importance to agriculture is the frequency of temperature above and below certain limits. For example, screen temperatures of 3°C indicate possible frost at ground level whereas maximum temperature of above 40°C indicate a point where plant enzymes break down and all growth ceases. A frequency analysis of temperature for the three main stations is shown in Table 5.2.

Table 5.2

Temperature Frequency - Qatar

(Average number of days/annum)

1972 - 79

Station	Mean Temperature				Mean Temp.	Max. Temp.		
	< 3°	< 7°	< 15°	< 20°	> 15°	> 35°	40°	45°
Rawdat al Faras	–	7	124	298	342	170	82	6
Decca (Abu Nkalah)	–	6	106	190	352	181	106	8
Abu Samrah	–	6	95	182	342	128	26	1

From these data, the extremes of temperature and the differences between the three stations are amplified. Computer plots of frequency of temperature and relative humidity at Rodiat el Faras and Abu Samrah are shown in Figs. 5.2 and 5.3.

The mean annual relative humidity is everywhere above 50% indicating conditions of high humidity throughout the year. Generally relative humidity during the winter months is of the order of 70% but gradually decreases to an average value of less than 50% under the influence of warm dry north westerly winds in April-May. There is however an abrupt increase in relative humidity at the end of July when the influence of the northern limit of the inter tropical coverage zone or monsoon front, lying at this time along the eastern Arabian coast and into the Arabian Gulf bringing no rainfall but doldrum type weather and very high humidities, reaching above 95% during the night. This increase in humidity does little however to ameliorate the high temperatures which frequently reach their highest annual mean value at this time of the year. Contrary to expectation there is a high diurnal variation on relative humidity; during the winter months it may vary from 40% to 75% but during the mid-summer months of June/July may fluctuate from 10% during the early afternoon to over 90% at night, particularly in the interior of Qatar.

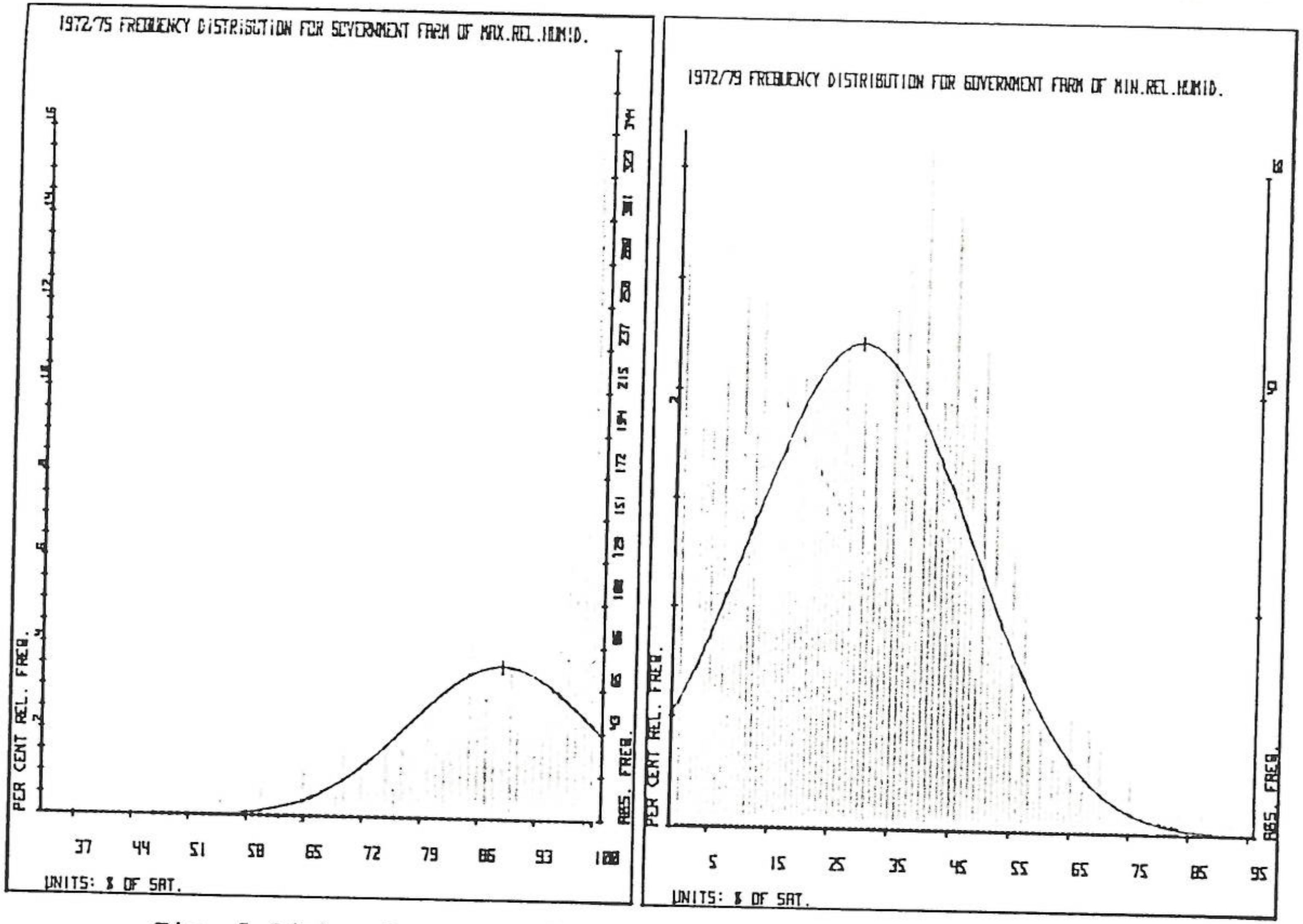


Fig. 5.3(a) Frequency distribution of maximum and minimum relative humidity

Rawdat el Faras

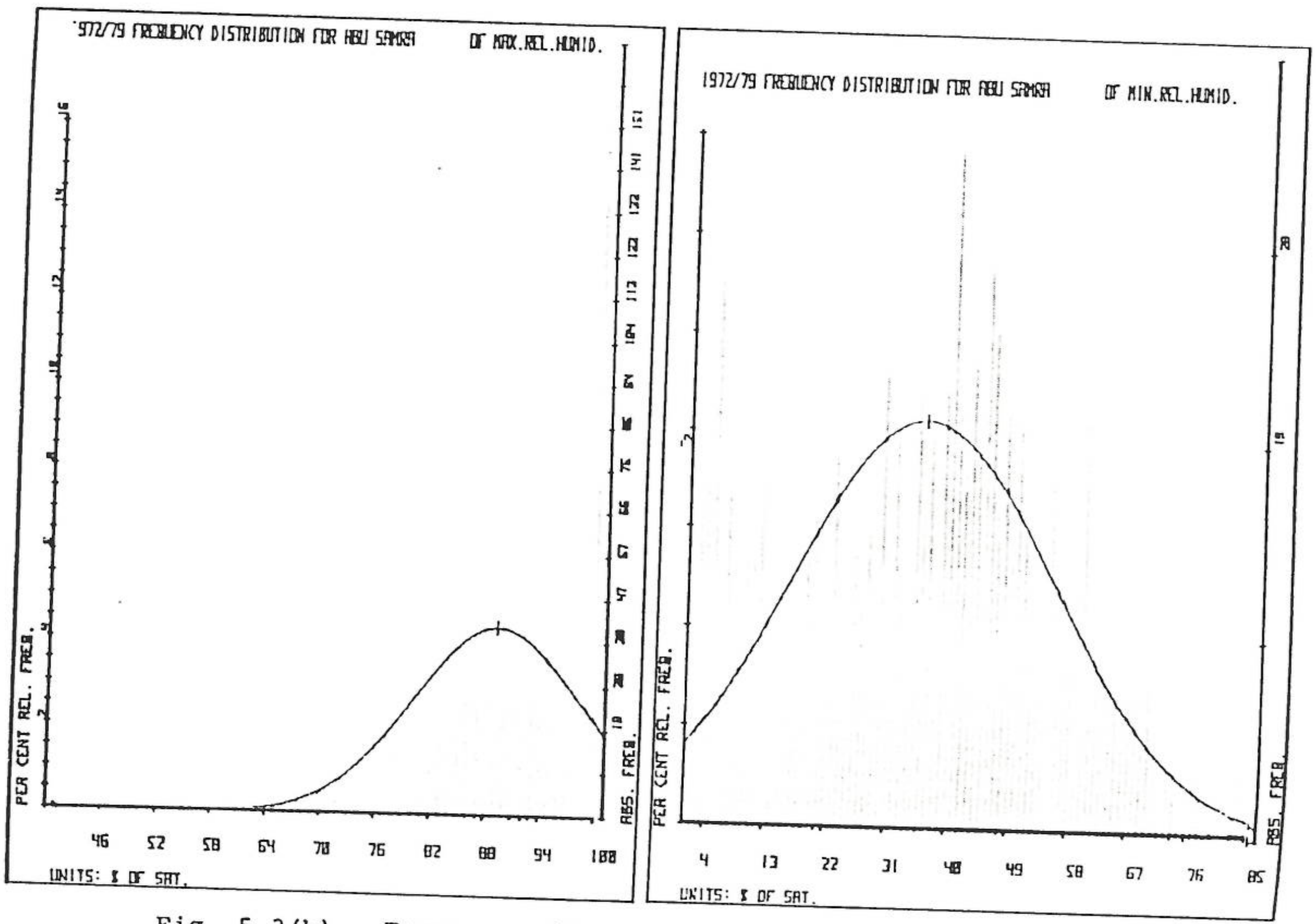


Fig. 5.3(b) Frequency distribution of maximum and minimum relative humidity

Abu Samrah

Table 5.3

Relative Humidity Frequency - Qatar

(No. of Days)

(1972-79)

Station	Min. R.H.			Mean R.H.	Max. R.H.		
	< 10%	< 20%	< 40%	< 50%	> 50%	> 60%	> 90%
Rodiat al Faras	63	123	251	300	363	355	158
Decca	102	180	303	108	359	344	147
Abu Samrah	45	90	202	325	364	360	189

5.4 RADIATION

As may be expected, gross incoming solar radiation is high throughout the year, varying from monthly mean mean values of 350 gm/cal/cm^2 in December to 650 gm/cal/cm^2 in June. Coupled with a latitude of 25^{O}N these high values of radiation provide for a very high light intensity for long periods with its adverse effects on the quality of agricultural produce.

5.5 WIND

Daily with run, expressed as km/day has been measured by totalising anemometers at Rawdat al Faras, Decca and Abu Samrah and at Doha Airport (in knots) for varying periods. During the winter months wind direction is variable with the predominant direction in December being NNE and in February SSE. However for the remainder of the year the predominant direction is NNW. During the winter months wind speed is generally low averaging 10-20 km/hour the daytime period but from March to the end of July there is a steady NNW wind of day time average speeds of 25-30 km/hr which, combined with rapidly rising temperature and decreasing daytime relative humidities has a marked effect on evaporation owing to its dessicating properties. This period is also marked by dust storms but generally these are not as severe as those experienced elsewhere in neighbouring Saudi Arabia owing to the limited fetch of the NNW wind over comparatively sand-free areas.

The prevailing dry NNW wind during the early summer months has the effect of increasing evaporation and is the principal climatic factor determining the micro-climatic difference between oases and open desert sites. The data from Decca and Rodiat el Faras provide clear evidence of these differences and the dominant role of windspeed. The former is located at an exposed open desert site whereas the latter is within a farm or oasis surrounded by windbreaks and vegetation, but both stations are located at the same elevation and distance from the coast, even though some 90 km apart. The following table shows mean values of various climatic parameters from which the dominant effect of wind speed is apparent.

Table 5.4

Difference in micro-climate between desert and oasis sites

(1972-79)

	Decca	Ridiat al Faras
Mean Maximum Temperature °C.	33.6	32.8
Mean Minimum Temperature °C.	19.5	19.1
Mean R.H. %	58.0	63.7
Mean Windspeed km/D	238.9	120.2
Mean Radiation gm/cal/cm^2	483	476
Total open water Evaporation mm	2526	2191
Total potential Evapotranspiration	2070	1744

Thus while temperature and radiation are nearly constant between the two sites, relative humidity is increased by 10% windspeed reduced by 50% and evapotranspiration by 16%. These differences illustrate the importance of establishing a good windbreak around irrigated areas within a desert environment. Without adequate windbreaks a small irrigated area in the desert will always be subjected to severe advection effects, which tends to increase evapotranspiration relative to assimilation and the efficiency of plant production. Comparing the situation in an irrigated area with that of the adjacent dry land, it is obvious that the extra water available causes more energy to be consumed in evaporation and less in heating the air and the soil. The temperature of the lowest layer of air is therefore reduced by irrigation, while the humidity of these layers is increased. In addition, the lower surface temperature leads to a reduction of emission of long-wave radiation from the ground. The degree of modification of the energy balance depends mainly on the irrigation rate, the dryness of the desert area and the rate of advection of warm dry air into the irrigated oasis.

To illustrate the effects of advection in a quantitative way we may take a typical day in March, mid-way between the winter and summer growing seasons in Qatar. Windspeed is at the order of 4 m/secs upwind conditions are dry with zero evaporation and the energy available for long-wave back radiation and sensible heat transfer is 23 m.cal/cm^2/sec. Absolute humidity is 10 g/m^3 and the air temperature at 2 m is 30^{o}C. The oasis area is assumed to be completely wet, with the albedo the same as that of the dry area and likewise the soil heat flux. Following a procedure first demonstrated by Philip (1960) a typical energy balance can be drawn for this situation as follows.

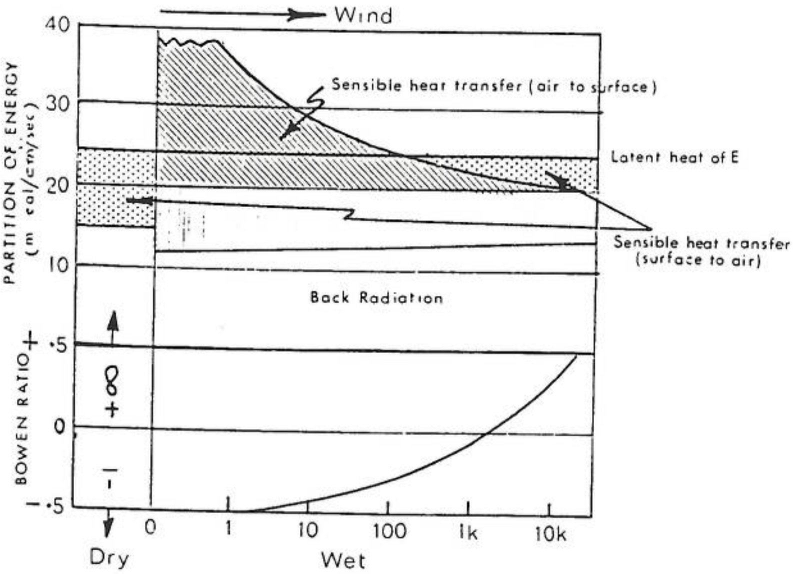


Fig. 5.4

Partition of energy in a typical Oasis

(after Phillip (1960))

One immediately obvious point is that the change in radiation balance is quite small and is obviously a second-order effect. The major effect is the violent change in the partition of the remainder of the energy between latent heat of evaporation and sensible heat transfer to the air. This is especially important immediately downwind of the leading edge but the region of advective inversion extends for over 1 km, so that at this point the heat flux is still from air to surface. Also, in this region of advective inversion of energy used as latent heat of evaporation may greatly exceed that available from the radiation balance. The excess is supplied by heat transfer from the air. These changes are reflected in the spatial variation of the Bowen ratio, the ratio of sensible heat transfer to the latent heat transfer. In the upwind dry area this ratio is ∞, immediately downwind of the leading edge it is -1 and remains negative for at least 1 km and thereafter continues to increase slowly.

The magnitude of the advection effect is obvious and it follows, from a viewpoint of water economy, it is advantageous to have a few larger irrigated areas instead of may scattered small areas as is, unfortunately, the case in Qatar. The adverse effects of advection in such a situation have been shown to be considerably overcome by the planting of windbreaks around irrigated areas and between fields with due regard to spacing to minimize the effects of downwind turbulence. The ameliorating effects are illustrated by the reduction in evapotranspiration by as much as 16% in the case of Decca and Rodiat el Faras.

5.6 EVAPORATION

Evaporation from an open water pan is widely used as an index of evaporation and evapotranspiration but the measured loss does not represent actual loss from an open water surface nor from crops and vegetation exposed to the same meteorological conditions. The standard evaporation plan in use in Qatar is the US Weather Bureau Class A pan, circular, of galvanized iron construction with a diameter of 122 cm and a depth of 25.4 cm. It is mounted on a 10 cm high, square wooden salt platform of a width which is slightly smaller than that of the pan. This type of pan allows heat transfer from the air and by direct radiation through the sidewells and from soil heat through the base, thus providing the pan with a heat source not found under natural conditions. From observations made in many parts of the world it has been found that a coefficient of between 0.68 and 0.75 should be applied to annual totals of evaporation pan loss to arrive at an estimate of natural open water evaporation. Because the effects of climate on the exposure of the pan will also vary with season, the annual coefficient cannot be applied to monthly data. Furthermore, experimental work in arid climates has shown that thus universally eccepted annual coefficient may not be valid and that it may fall as low 0.55 under severe conditions. In Qatar evaporation pans have been equipped with a wire mesh screen to prevent damage and loss by birds and animals and this has had the effect of reducing direct radiation and therefore raising the pan coefficient. Data from three stations show that the annual pan coefficient may vary from 0.65 to 0.70 which is close to the generally eccepted value for a normal open class A pan. The screen therefore partially offsets the increased advective effects.

In calculating true open water evaporation values therefore, a combined energy balance - aerodynamic approach first proposed by Penman (1948) has been used. The Penman equation has been widely used by practising hydrologists and needs little introduction. In devising the equation, Penman successfully combined the energy balance and mass transfer equations in order to avoid specifying conditions at the surface and to utilize readily available standard meteorological data in the form of radiation or sunshine hours, temperature, relative humidity and windspeed. Investigations by Tanner and Pelton (1960), Businger (1956) and van Bavel (1966) have confirmed that the basic formula provides a sound physical model that takes into account both vertical and horizontal energy components, the latter being of significance under strong advective conditions. It is only when the basic model is applied to various crop surface under severe advective conditions that inaccuracies arise, an aspect fully discussed in Sec. 5.7 below.

The original Penman (1948) equation may be written in expanded form as :

$$Eo\ (mm/day) = \frac{\Delta}{\Delta + \gamma} Ra(1-r).(a+b\ n/N)$$

$$= - \frac{\Delta}{\Delta + \gamma} \sigma\ Ta^4 (0.56-0.092 \sqrt{e_d}) (0.10+0.90\ n \sqrt{N})$$

$$+ \frac{\gamma}{\Delta + \gamma} 0.35(1+ \mu/100) (e_a - e_d)$$

where

Δ = Slope of the saturation vapour pressure curve at mean air temperature mb/°C.)

γ = Constant of the wet and dry bulb psychrometer eq. (mb/°C.)

Ra = Theoretical incoming short wave radiation at the limit of the earth's outer atmosphere (mm/water)

r = Reflection coefficient or albedo (%)

n = Actual hours of sunshine (hrs)

N = Theoretical maximum duration of sunshine (hrs)

σTa^4 = Black body radiation at mean air temperature in °K (mm)

e_d = Mean vapour pressure (mm Hg)

e_a = Saturation vapour pressure (mm Hg)

μ = Wind run at 2 m (km/day)

The three terms represent, respectively, the incoming shortwave radiation (Ri), the out-going long-wave radiation (Rb) and a bulk aerodynamic term (Ea). The dimensionless factors $\Delta / \Delta + \gamma$ and $\gamma / \Delta + \gamma$ make allowance for the relative significance of net radiation and the aerodynamic terms in total evaporation. In the original derivation it was assumed that these weighting factors were functions of mean air temperature alone, but work in East Africa by McCulloch (1965) indicated that these factors have a marked dependence on altitude. In Qatar the altitude correction has been neglected and the sunshine/radiation term substituted by direct observations of gross incoming radiation thus improving the accuracy of the estimate.

Annual totals of openwater evaporation in Qatar have been calculated from meteorological data from Rodiat el Faras, Decca and Abu Samra and shown to vary from 2191 mm to 2526 mm and Table V presents mean monthly open water evaporation totals for these three stations.

Table 5.5

Mean Open Water Evaporation (Penman) - Qatar

(mm)

(1972-79)

Station	O	N	D	J	F	M	A	M	J	J	A	S	Ann.
Rawdat al Faras	173	124	96	93	102	152	185	243	278	277	252	213	2191
Decca	197	143	113	111	114	176	225	286	312	314	294	240	2526
Abu Samrah	185	139	112	112	113	164	204	250	263	251	249	215	225[illegible]

Daily evaporation rates therefore vary from 2.5 mm/day during the winter months to 11.5 mm/day during the summer. The variation of open water evaporation throughout the year is the integrated sum of the effects of temperature, radiation, humidity and wind and their interaction at various sites results in the minor variations of monthly values.

.7 EVAPOTRANSPIRATION

.7.1 Irrigation Crop Water Requirements

Evapotranspiration and irrigated crop water requirements in Qatar are of considerable importance in any assessment of the water resources and their development where 80% of all roundwater extracted is utilized for irrigation. In calculating evapotranspiration and crop ater requirements however a number of difficulties arise. Firstly, the Penman formula for vaporation, although widely used for calculating crop water requirements, is based on the oncept of 'potential evapotranspiration' and secondly, it refers to a short green crop (i.e. hort grass). Both these assumptions severely limit the straightforward application of the equation under arid conditions. Potential evapotranspiration assumes a non-limiting water supply and maximum growth requiring full use of available water. In practice in an arid zone : is not usual to apply that treatment which gives the masimum yield to be adopted as the optimum, not only for economic reasons but also because, where availability of water is restricted it is important to obtain maximum yields per unit of water. The concept of potential apotranspiration as applied to irrigation control therefore becomes largely irrelevant under ..e arid conditions of Qatar. It does however provide a useful point of reference in the context of the climatic and geographic factors prevailing at any given point. By considering timum economic water use rather than potential evapotranspiration rates, the problem is ndered much more complex since it introduces the physiological factors that determine how crop yields respond to water application. Water requirement experiments in arid zones have own that different crop species exhibit quite different responses to the same range of rigation treatments so that optimum economic water use varies widely in the same climatic or geographic conditions. For example, experiments in Qatar have shown that optimum water for tomatoes is of the order of 0.6 of the potential rate (Dastane et al, 1978). A ber of of physical and physiological factors cause these differences and, among them, the most important is probably the different responses of the growth and transpiration processes increasing water stress.

Experimental work by Van Bavel (1966) in Arizona clearly demonstrated the basic validity Penman equation when applied to evapotranspiration but at the same time showed the need for dification in the aerodynamic term under severe advective conditions. This arises from ious factors commented upon in the preceding paragraph out also because of the various hness Coefficients of different crops at all stages of growth. He proposed a different dynamic term based on wind profile theory that accounts for increased evapotranspiration r advective conditions. However, the data requirements for this modification are somewhat exacting and are not generally those readily available. In order to compute evapotranspiration various crops as a reference point and taking into account these additional factors, a lified approach has been adopted. This is based on the recommendation of a Working Group on Crop Water Requirements set up by FAO in 1972 and published in FAO Irrigation and Drainage r No. 25 by Doorenbos and Pruitt (1975). This procedure consists of computing potential otranspiration by Penman with an appropriate albedo for a green crop (≈25%), designated Eto. This value is then modified to take into account the variation of day and night time windspeeds correction factors based on the prevailing regime of temperatures, wind and humidity to ide a value of Eto* known as modified potential evapotranspiration. From a knowledge of he growing season of each local crop, factors that take into account the various stages of owth of each crop type selected from a comprehensive list of crop factors computed from world experience, are then applied to values of Eto*. These crop factors successfully combine uch additional variables as crop height and physiological factors.

The Doorenbos and Pruitt version of the Penman combination method was tested over 3-year od in an arid environment under extreme advective conditions by Shonse, Jury and Stlzy 980) and found to correspond closely to measured values. Four other empirical and determi- formulae tested at the same time exhibited degrees of difference, with pan evaporation A) showing the greatest divergence. However, Faulkner and Evans (1981) in testing this sion by an energy balance method over irrigated crops in eastern Saudi Arabia, confirmed a e of agreement in advection and the oasis effect but found that the Doorenbos & Pruitt equation overestimated evapotranspiration by 25% on a 24 hourly basis. This is to be expected as the original Penman equation, and its subsequent modifications were not intended for use for periods of less than 10-days.

Monthly values of Eto* together with Eto/Epan ratios are given in Table 6. The Eto* data given in this table are computed from data at Rawdat al Faras experimental station in northern Qatar, considered to be generally applicable to irrigated agriculture within a typica oasis area. The values computed from open desert sites at Decca and Abu Samrah are in effect irrelevant because the basic climatic parameters of wind and humidity would themselves be altered under the micro-climate effects of irrigated agriculture.

Table 5.6

Mean Monthly Values of Eto*

(Modified Potential Evapotranspiration)

(mm)

(1972-79)

	O	N	D	J	F	M	A	M	J	J	A	S	Ann.
Eto*	137	94	71	70	78	120	145	190	220	222	206	173	1727
Eto*/Eo	.79	175	174	.75	.76	.78	.78	.78	.79	.80	.82	.80	.75
Eto*/Ep	.79	.79	.86	.90	.91	.78	.68	.60	.55	.57	.63	.72	.67

The variation in monthly Eto*/Epan ratios reflects the dominant effect of wind speed and humidity. The ratio decreases steadily from February to June/July under the influence of increasing windspeed and reduced relative humidity but increases abruptly at the end of July with the onset of a high relative humidity and decreased windspeed. These ratios provide a useful method by which Eto* may be approximated directly from Epan data as a basis for computing crop water requirements.

Daily Eto* values range from 2.5 to 9.5 mm, the high rates being maintained for approximately 60 days from the end of May to the latter end of July when plant growth is adversely affected, irrespective of the amount of water applied. Few plants are capable of taking up water at a rate in excess of 9 mm per day and from a purely physical point of view it is clear that prevailing rates of evapotranspiration in the summer months impose a major constraint to irrigated agriculture in Qatar.

In computing crop water requirements the ten-day values of Eto* from Rawdat al Faras have been taken as a standard reference. To these values crop coefficient data provided in FAO Irrigation and Drainage Paper No. 24 (Doorenbos and Pruitt) p. 65 have been applied, as shown in Table 5.7. Table 5.8 summarizes net crop water requirements in mm/10 day period or m^3/donnum/10 day period. To these values must be added leaching requirement (if necessary), conveyance and field application losses, (See Project Technical Report No. 4, Irrigation Practices by Dastane and Al-Faihani).

Table 5.7

Crop Coefficients (kc) - Qatar

Crop		Initial Stage	Development Stage	Mid Season	Late Season	Planting Date
Wheat/Barley	d	20	30	60	30	Dec. 1
	kc	.40	1.10	1.15	.20	
Tomato	d	55	70	75	60	Aug. 20
	kc	.60	1.05	1.05	0.6	
Squash (Spring)	d	28	20	28	20	Feb. 25
	kc	.60	.70	.95	.75	
Squash (Autumn)	d	18	20	38	9	Sep. 15
	kc	.60	.70	.95	.75	
Melons (Spring)	d	25	21	30	35	Mar. 25
	kc	.60	.80	1.0	.75	
Melons (Autumn)	d	25	15	40	30	Aug. 5
	kc	.70	.85	.95	.65	
Sweet Corn	d	14	25	23	13	Feb. 20
	kc	.5	1.0	1.1	1.0	
Cucumber (Spring and Autumn)	d	30	23	15	37	Feb. 21
	kc	.65	.65	.75	1.0	Aug. 1
Crucifers	d	38	40	31	21	Sep. 10
	kc	.50	.75	1.05	.90	
Okra (Spring)	d	22	27	48	41	Mar. 20
	kc	.70	.85	1.05	.85	
Okra (Autumn)	d	27	34	44	54	July 20
	kc	.70	.85	1.0	.90	
Sweet Pepper	d	67	33	165	71	Mar. 20
	kc	.60	.85	1.05 - 1.00	.85	

7.2 Energy-Balance Studies

Although the validity of the Penman equation for potential evapotranspiration and modifi- :ions made by Doorenbos and Pruitt (1975) has been shown to apply to a wide range of climates l conditions, no original verification work has as yet been carried out in the Arabian Gulf region and in particular in oasis situations with a very larger advective component from hot, surroundings. In September 1979 energy-balance instrumentation was installed over an alfa field at Wadi el Araig experimental farm in south-western Qatar, 5 kilometers inland from the coast and set within an extensive sand-dune and sabkha area and has been operated more less continuously since then.

The objective of these studies is to determine the energy balance over a field of alfalfa Jn a continuous basis and calculate evapotranspiration by the Bowen ratio method. Instrument- on consists of two pairs of temperature and dew point sensors set at 0.5 and 1.0 m above the rop surface (raised and lowered with crop growth and cutting) a net radiometer and a soil heat lux plate. Each parameter (air temperature, temperature difference, dew point, dew point ference, net radiation and soil heat flux) is continuously recorded on EPR recorfers set in air conditioned house on the edge of the farm

REQUIREMENTS – QATAR (mm ... period) ... able

PERIOD	WHEAT BARLEY	ALFALFA	DATES	CITRUS	SUN-FLOWER	SUGAR-BEET	CUCUMBER	SQUASH	MELONS	TOMATO	OKRA	SWEET-PEPPER	CRUCIFERS
July 1		94.5	31.5	49.5							76.5	90.0	
2		111.2	31.1	48.9							76.5	89.0	
3		25.0	28.2	45.3							67.1	75.0	
Aug. 1		77.7	25.9	40.7			48.0		51.8		55.5	77.7	
2		93.7	26.2	41.2			48.0		55.5		59.2	78.7	
3		22.1	25.7	40.5			44.2		59.8	43.6	63.6	70.3	
Sep. 1		65.1	21.7	34.1			42.1		49.6	40.8	55.8	62.0	
2		75.0	21.0	33.0	29.0		40.6		55.1	38.4	55.1	60.0	29.0
3		17.4	20.3	31.9	27.0		40.5	32.4	51.3	36.0	54.0	58.0	27.0
Oct. 1		52.5	17.5	27.5	25.0		37.5	30.0	47.5	32.5	50.0	50.0	30.0
2		58.7	16.5	25.8	28.2		35.2	28.2	44.6	33.5	47.0	47.0	28.0
3		20.2	16.1	27.8	32.3	30.4	36.9	35.5	37.9	35.4	46.0	46.0	35.2
Nov. 1		38.0	12.0	20.0	41.0	24.6	28.7	36.9	26.6	30.1	38.9	40.0	28.7
2		42.6	11.1	18.5	40.0	26.6		35.1		32.3	34.2	37.0	30.4
3		12.5	10.5	17.5	36.7	24.5	400	33.2	480	33.2	31.5	35.0	31.5
Dec. 1	2.4	31.3	9.9	16.5	12.8	25.6		24.5		31.0	28.8	29.7	32.0
2	9.2	32.2	8.4	14.0	12.0	27.0		20.2		31.5	27.0	25.2	31.5
3	11.7	10.5	7.9	13.2	10.0	25.0		280		28.8	22.5	23.7	28.8
Jan. 1	17.9	22.8	7.2	10.8		26.4				26.2	670	20.4	24.0
2	22.1	32.2	8.4	12.6		30.8				31.5		22.4	25.2
3	21.8	11.9	8.9	12.1		29.7				34.6		23.8	
Feb. 1	29.1	27.0	9.0	13.5		33.0				30.4		24.0	
2	47.9	41.0	10.8	16.2		39.6				30.4		28.8	
3	46.0	13.6	10.3	15.2		36.0	22.4	20.6		35.2			
Mar. 1	61.6	42.0	13.2	22.0		48.6	29.2	27.0		46.4			
2	58.2	57.5	15.0	25.0		41.6	21.0	29.4		50.0			
3	52.0	17.8	16.5	30.2			41.1	42.3	36.3	60.5	42.3	36.3	
Apr. 1	56.0	68.2	12.6	32.5			45.5	58.5	39.0	58.5	45.5	39.0	
2	34.5	88.7	21.3	35.5			53.2	67.4	50.0	59.5	56.8	49.7	
3	26.1	24.6	24.6	41.0			61.5	77.9	65.6	60.0	69.7	65.6	
May 1		82.9	27.6	41.0			59.2	75.0	71.1	56.2	71.1	63.2	
2		102.5	28.7	41.0			61.3	63.0	84.0	58.8	84.0	69.7	
3		30.0	31.8	50.0			70.0	68.2	100.0	64.3	105.0	77.3	
June 1		95.5	31.8	45.5			465	530	91.0	54.0	105.0	77.3	
2		113.7	31.8	45.5					87.3		105.0	77.3	
3		25.2	29.4	42.0					68.0		105.0	75.6	
ANNUAL	495	1175	695	1075	295	470	-	-	690	1200	1070	1745	[illegible]

Note: (1) Alfalfa assumed cut every 20 days. (2) Sub totals in column refer to separate plantings.

Project computer for which a special set of programmes were developed to digitize the original charts and compute the energy balance at hourly intervals. Analysis of the results of this investigation were not available for inclusion in this report but will form the subject of a special research paper in 1982.

.7.3 Evaporation from Sabkha

Work in eastern Saudi Arabia (Italconsult, 1969, FAO 1979) has shown that the consider-ible areas of coastal and inland sabkha in that region are evaporative sinks for both deep groundwater by a process of upward leakage and by lateral inflow of shallow **phreatic** ground-water. From a number of energy balance determination on the Sabkha An-Nabiyah, near Dharhan, n the winter and late spring of 1969, Pike (1970) estimated the evaporation of groundwater o be of the order of 0.7 meter/annum^{-1} or 0.40 of the annual potential evaporation from a wet soil surface (albedo$\approx$0.33). When this depth was applied to the considerable areas of ctive sabkha throughout the region the total evaporation loss was found to be of the order f 500 x $10^6 m^3$.

5.8 RAINFALL

5.8.1 Introduction

Rainfall over Qatar is the primary source of freshwater and a knowledge of its amount, variability and distribution is of fundamental importance in any assessment of the country's water resources. Rainfall is confined to the winter months of November to March but in some years outbreaks of thunderstorms have occurred as early as September and October and as late as the latter end of April. In general rainfall is of two types; winter storms confined to the period December - February and covering the whole country with high intensity cells or early and late winter thunderstorms of localised high intensity. Variations in the distribution and intensity of winter storms have been observed with a tendency for higher falls to be recorded in the extreme north and the south western areas.

Total average rainfall over Qatar may vary from 10 mm to over 200 mm in any one year but falls from individual storm events sometimes as high as 180 mm in 4-5 days (1964) have occurred. The modal annual rainfall would appear to be of the order of 75 mm in northern Qatar and slightly less in southern Qatar.

5.8.2 Long-term Rainfall Characteristics

The only reliable long term data available are those recorded at Bahrain (50 years) and at Doha (22 years). On the basis of these two records an analysis of their statistical properties has been undertaken to define their distribution and determine the frequency probability and variability of annual totals.

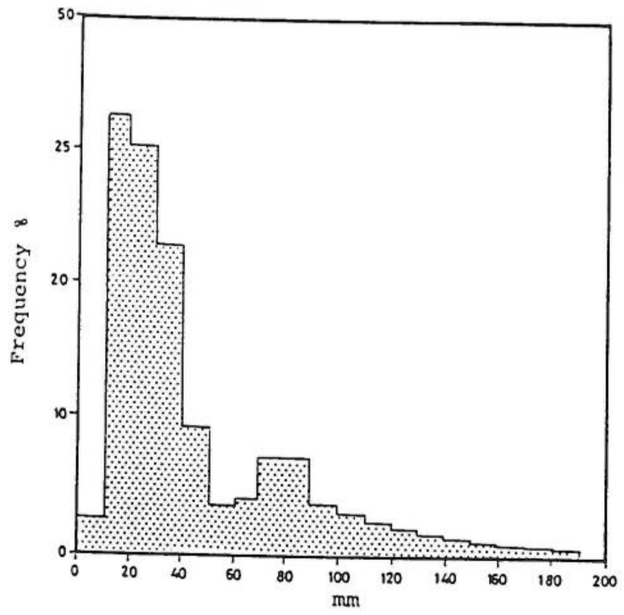


Fig. 5.5

ANNUAL RAINFALL FREQUENCY
DISTRIBUTION - DOHA

A frequency distribution graph for the long-term Doha record is shown in Fig. 5.5 and it is clear that annual rainfall is not normally distributed and shows a strong positive skewness with pronounced leptokurtosis and a double peak, a type of distribution commonly found in desert and semi-arid zones. In such cases it is necessary to fit a distribution that accounts for this skewness and a number of distributions (i.e. gamma, Pearson types I & III or extremal types) may be utilized for this purpose.

In the first instance the data were fitted to a log-normal type distribution but both data arrays exhibited a pronounced 'dog-leg' which would indicate that rainfall occurences are derived from two different meteorological systems and which may well be the case; lower totals from Mediterranean type cold front rainfall and higher totals from Arabian Gulf boundary front high intensity rainfall in the early and late winter months.

Resort was therefore made to an extreme value type probability function in an effort to define a distribution which would provide the basis for any stochastic type storm model. The extreme value probability theory is based on the work of Fisher and Tippet (1928) and applied by Gubel (1941) to hydrologic analysis, particularly in flood studies. Extreme value probability is based on the finding that the distribution of the N largest (of the N smallest) values, each of which is selected from one of the m values contained in each N samples, approaches a limiting (asymptotic) form as m is increased indefinitely. The type of the limiting form depends on the type of the initial distribution of the Nm values, and three different asymptotes can be derived. The extreme value distribution of an exponential type may be written as

$$p(x) = \frac{1}{c} e^{-(a+x)(c-e^{-(a+x)/c}}$$

with 79/80 $-x < x < oo$, where x is the variate and a and c are parameters. The cumulative probability is

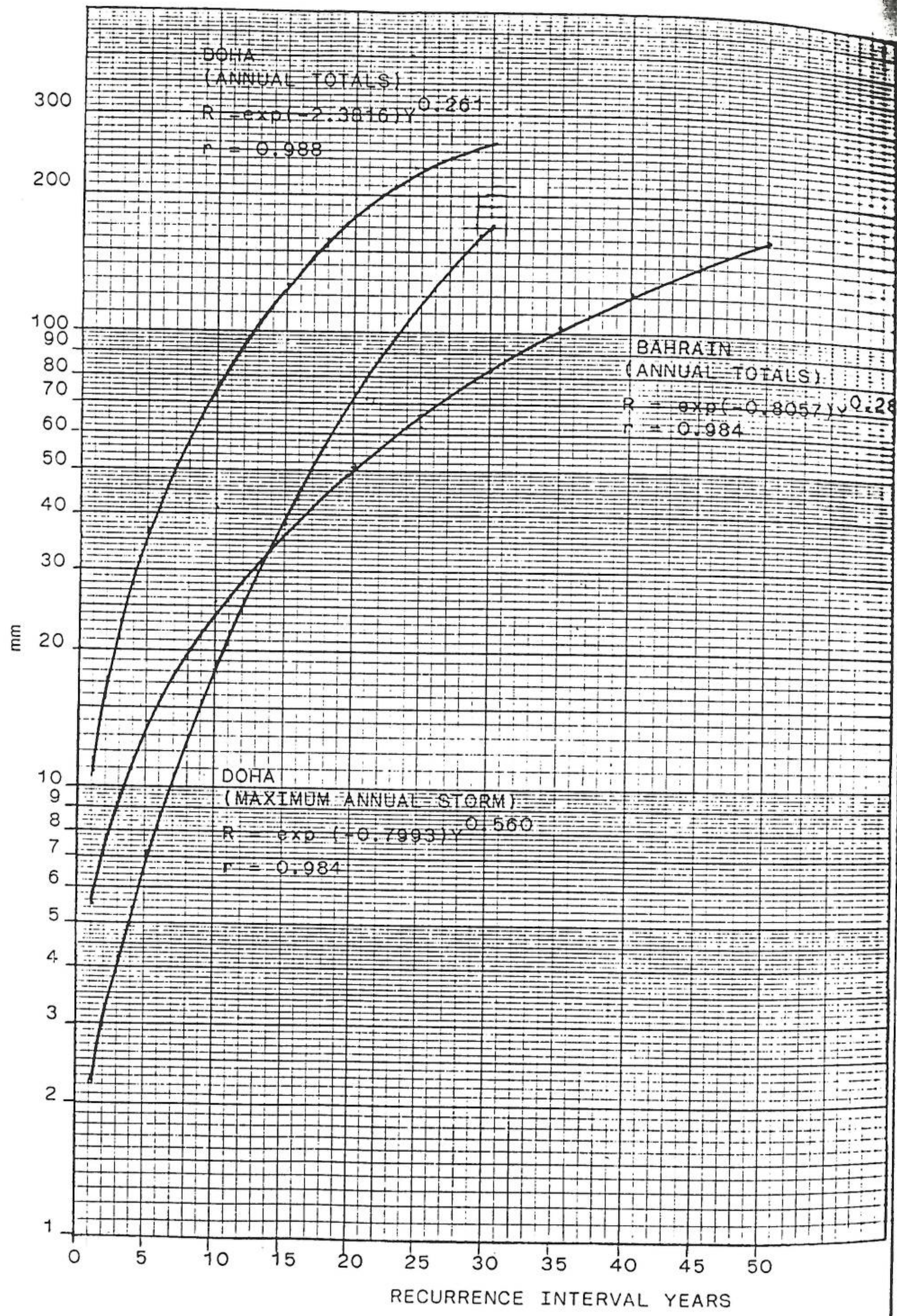
$$p(a+x) - e^{-(a+x)/c}$$

This distribution was applied to the series of maximum annual rainfall in each year at Doha or storm events irrespective of whether these occurred on one or more days. The distribution shown above did not fit these observed data and was replaced by a log extremal type distribution where the variate x is replaced by a linear function of the logarithm of $x - \Sigma$, which is type III extremal distribution (sometimes known as a Weibull distribution) and the cumulative frequency is written as

$$P(X < x) = e^{-}\left[(x - \Sigma)(\theta - \Sigma)\right] k$$

where $-D < x \leqslant \Sigma$. The parameter k is the order of the lowest derivative of the probability function that does not vanish at $x = \Sigma$, and θ is the expected largest value.

This distribution closely defines the frequency of both storm and annual rainfall series, plots of which are shown in Fig. 5.6. This confirms an earlier finding by Sariahmad and Kisiel (1970) that rainfall in arid zones tends to conform to a Weibull type distribution. Table 5.9 summarises statistics and the probabilities derived from this analysis. This also shows the clear difference between observations made at the Water Department Laboratory and the Doha Airport. The fact that they are only 1 km apart suggests that the data are at fault. For instance, on 2 February 1968 a strong cold front moved down the Gulf and over Qatar and heavy rainfall (40-50 mm in two days) was recorded at Bahrain and Sharjah. The Water Department record have no observation of rainfall on this day whereas 40.4 mm was observed at the Airport. Similarly, in April of the same year the difference was 2.0 and 27.8 mm. This, and other discrepancies noted, suggest that the airport record is the more reliable record. While this discrepancy may at first sight appear to be of little consequence it is of the greatest importance in extending the record of recharge to groundwater by correlation techniques, details of which given in later in this chapter and elaborated



ANNUAL & STORM FREQUENCY - WEIBULL DISTRIBUTION

Fig. 5.6

Although the long-term mean annual rainfall at Bahrain and Doha are of the same order, the frequency of both higher total storm and annual rainfall at Doha is three times greater. It is also of interest to note that an individual storm may account for up to 65% of the total fall. Heavy storms of over 150 mm in 2 to 3 days (such as that which fell in December 1964) have a average frequency or return period of 30 years and the recurrence of such a storm could flood large areas of the municipal area of Doha because of a lack of adequate storm water drainage.

Table 5.9

RAINFALL STATISTICS AND PROBABILITY

DATA (BAHRAIN AND DOHA)

	BAHRAIN	DOHA 1	DOHA 2	DOHA 3
Years of Record	50	21	17	17
Maximum Rainfall	186.1	190.7	229.7	172.0
Minimum Rainfall	16.1	2.0	12.2	12.0
Mean Annual Rainfall	75.1	62.8	80.44	–
Standard Deviation	45.8	51.3	59.6	–
Coefficient of Variation %	61.0	81.2	74.5	–
Weibull Correlation	0.984	0.933	0.971	0.983
t - Stat	17.65	11.31	15.81	74.55
Significance	0.01%	0.01%	0.01%	0.01%
Recurrence Table Yrs. 5	15	13	37	7
10	26	41	77	18
15	38	96	126	38
20	52	198	184	72
25	67	225	240	120
30	83	–	–	170
35	101	–	–	–
40	121	–	–	–
45	142	–	–	–
50	164	–	–	–

Doha 1 = Water Department
2 = Airport
3 = Maximum Storm

.8.3 Annual Rainfall over Qatar 1972-80

Daily type raingauges were installed at Doha and five municipal well-fields in east entral Qatar in 1958 and this was follwed by the installation of 24 raingauges on a wider network throughout the country in 1971/72 by the Project. In 1976 ten automatic recording aingauges were substituted at some of these stations and an additional three combination ater level/rainfall recorders were also installed (see Fig. 5.1). Rainfall records are onsidered to have been reasonably reliable up to 1973 when there was a serious deterioration n the standard observation. In 1974 the Project made a concerted effort to improve the uality of observation and frequency of supervision. (Pike et al, 1975). This deterioration n the quality of records is most unfortunate as almost all the longer-term stations were so ffected and furthermore the intermittent nature of the data collected led some workers to onclude that rainfall over Qatar was extremely sporadic. Subsequent enquiries instituted y the Project have however shown that this is not the case; the observations were sporadic, ot rainfall. Current procedures include the regular inspection of all installations, regular intenance and the checking of all observes immediately after rainfall.

While it has been argued (in the case of the two Doha records) that even at a distance of 1 km significant differences in annual rainfall amount may occur, this is not borne out by a computer-based analysis of data (1974 onward) from the existing raingauge network. The purpose of the investigation was to provide data upon which a modification to the network could be based, assist in logical data validation of further rainfall and to substitute missing data. The results of this analysis are given in Technical Note No. 4 (NS) (Correlations in the Qatar Raingauge Network by M.W. Rogers, 1979). Forty stations were considered in 820 coupled combinations by linear regression which showed a high degree of correlation between stations in a radius of 60 km in northern Qatar and in a smaller radius in southern Qatar. This conclusion tends to confirm the observation of a more general and widespread rainfall pattern of northern Qatar.

In a report prepared by ECWA (Introduction of an Adequate System for Collecting, Computing and Analysis of Water Resources Data in the Near East (1978)) Qatar is listed as having the 'best raingauge and hydro-meteorological from both density and distribution in the region'. Coupled with the correlation analysis referred to above this would suggest that the network could be reduced to about 12 stations only to provide an accurate measure of annual rainfall. However, accurate data on daily and hourly rainfall is often required for recharge studies and the present network should therefore be maintained.

Annual rainfall, deduced from these records and adjusted where necessary for each of the years 1972-79 is shown in Table 5.10 and for each of years as a isohyetal plot in Fig. 5.7 (a to h). Fig.5.8 shows the deduced annual average rainfall over Qatar for the period 1972-79. With a coefficient of variation of annual rainfall of the order of 75% the term 'average rainfall' is apt to meaningless and the isohyetal map presented is merely the mean of annual rainfall totals observed at 15 stations over a 9 year period and provides, at best, an indication of relative amounts of rainfall over the country. From these data the following is concluded;

- The land mass of Qatar, protruding into the Arabian Gulf, appears to be of sufficient extent to provide convection to easterly moving air streams in the winter and more isolated and comparatively intense thunderstorms during the early and late winter. Generally, annual totals tend to be higher in the northern and central areas than along the coasts in winter although during the spring months there is a tendency for thunderstorms to build up over the east coast, possibly as a result of boundary front conditions.

- The maximum rainfall over Qatar occurs as a cell situated in the north central part of the country and coinciding with the main northern recharge area.

- The minimum rainfall is found along the west coast southward from Dukhan which appears to lie in the rain shadow of higher ground to the west in Saudi Arabia. The Dukhan range does not appear to exert an orographic effect.

- Northern Qatar tends to receive an average about 30% more rainfall than southern Qatar.

From these data the average depth of rainfall over the country as a whole for each year has been calculated and further sub-divided into northern and southern sectors. The northern sector corresponds to an area of 3770 km^2 in north central Qatar and bounded by the limestone facies boundary referred to in Chapter 3.

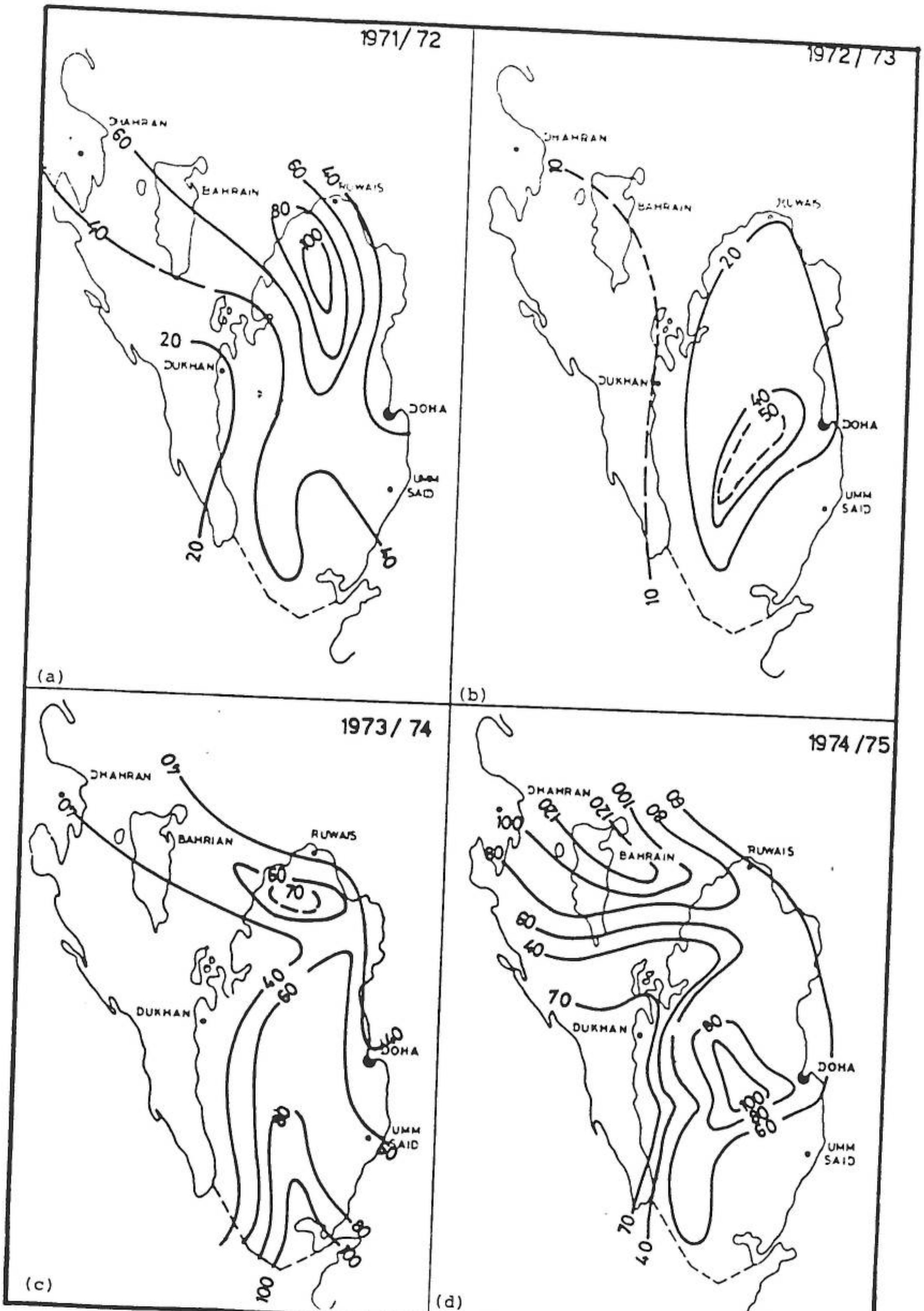


Fig 5.7 (a-d) Annual Rainfall Distribution 1971-75

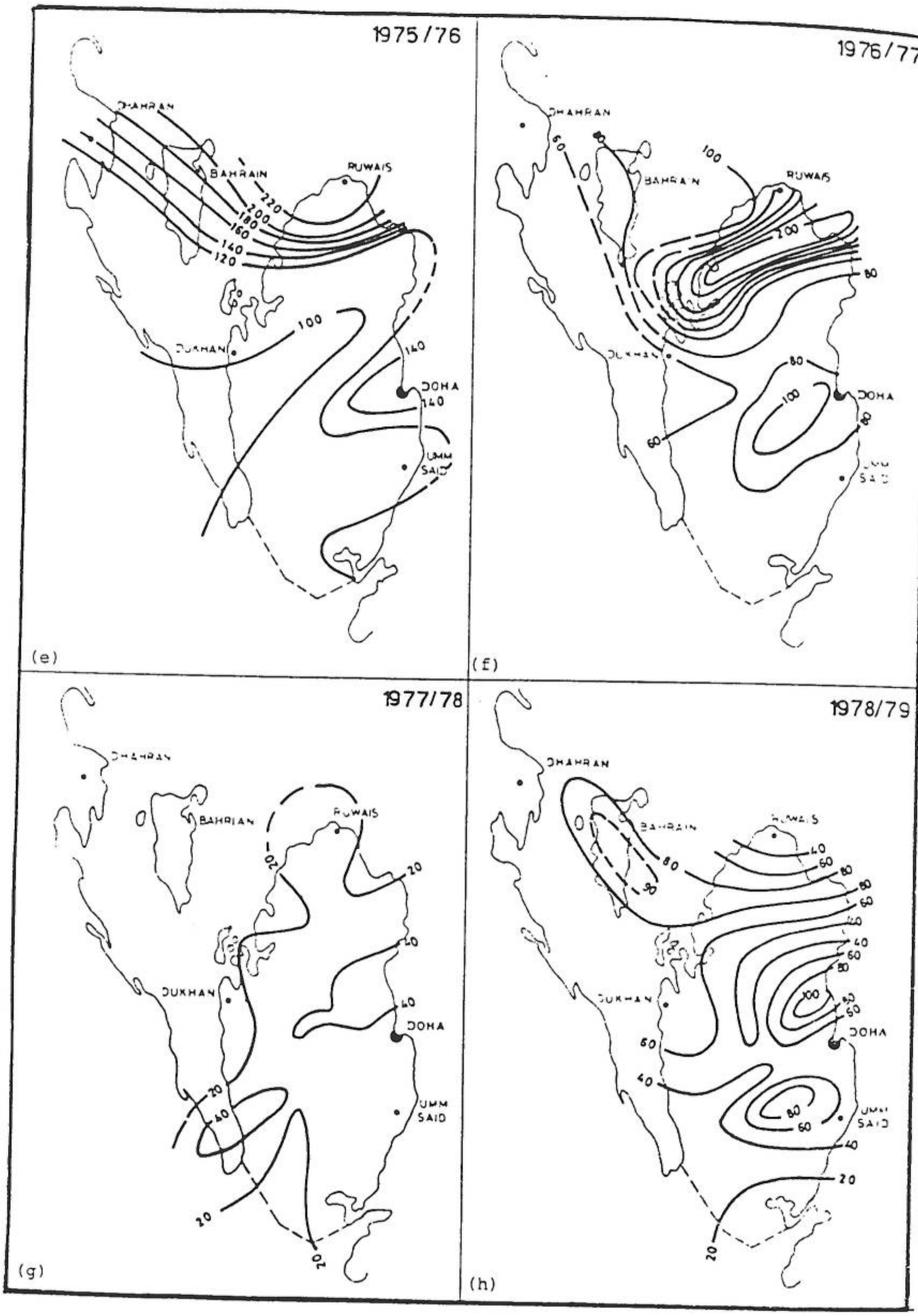
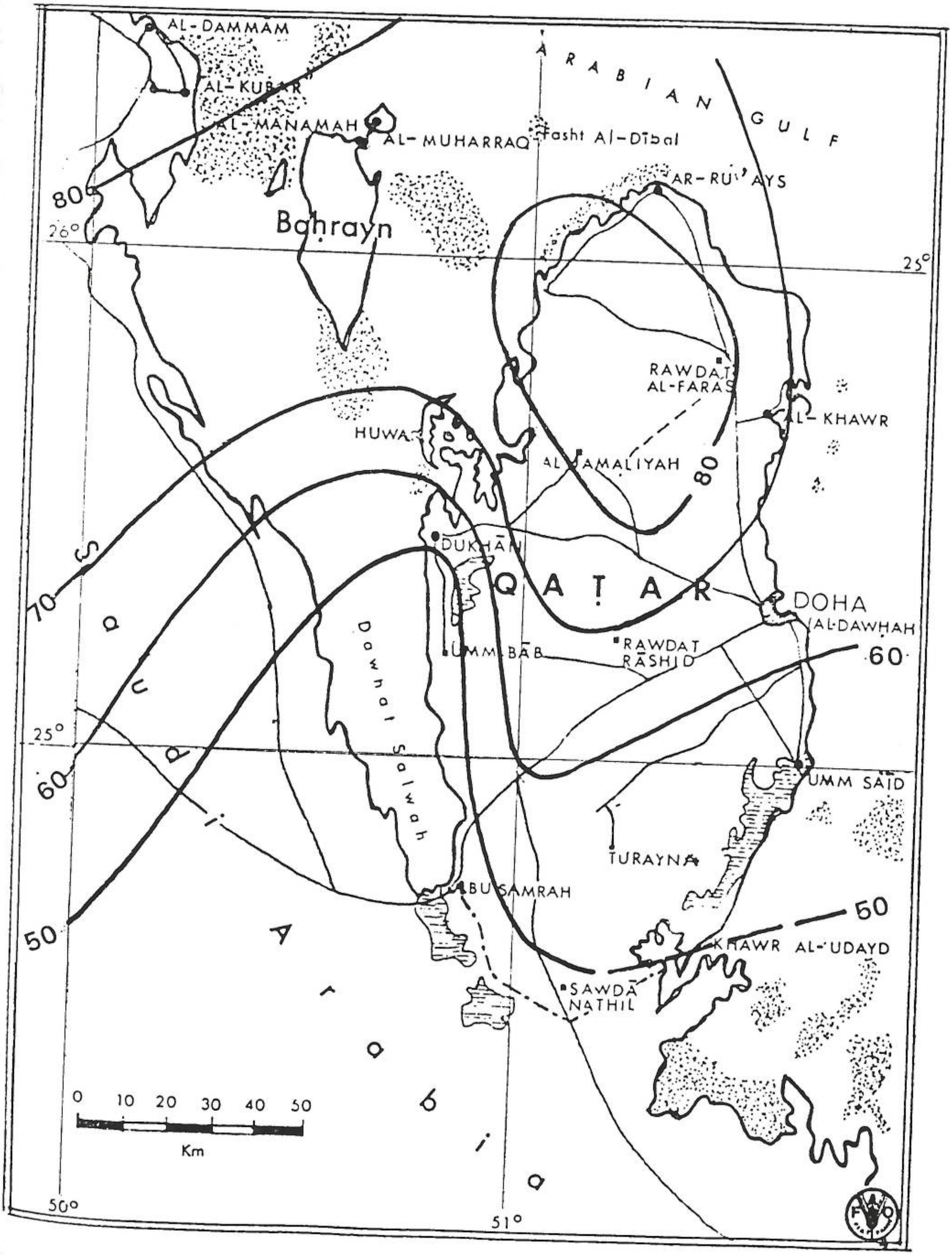
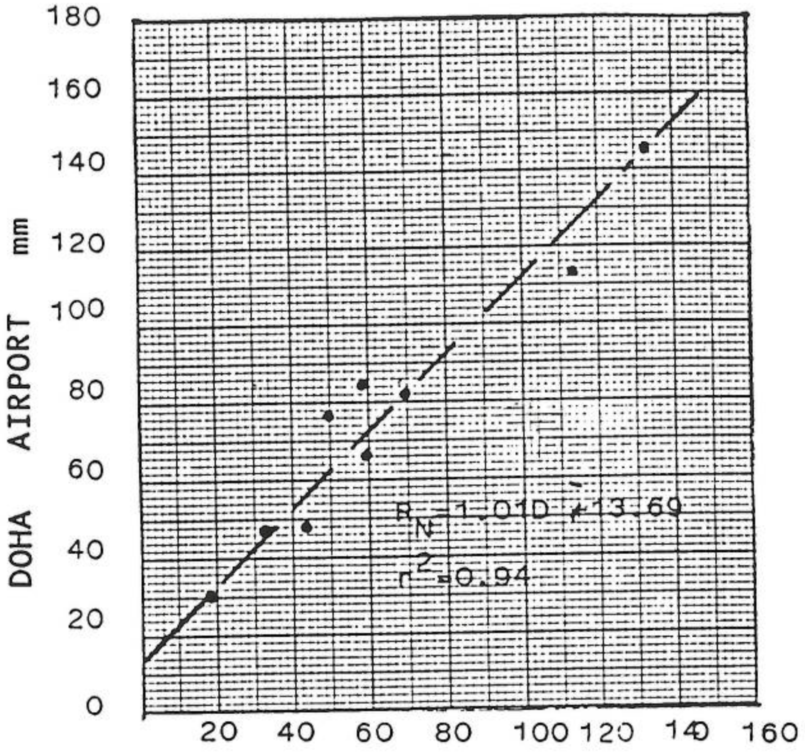


Fig 5.7 (e-h) Annual Rainfall Distribution 1975-79

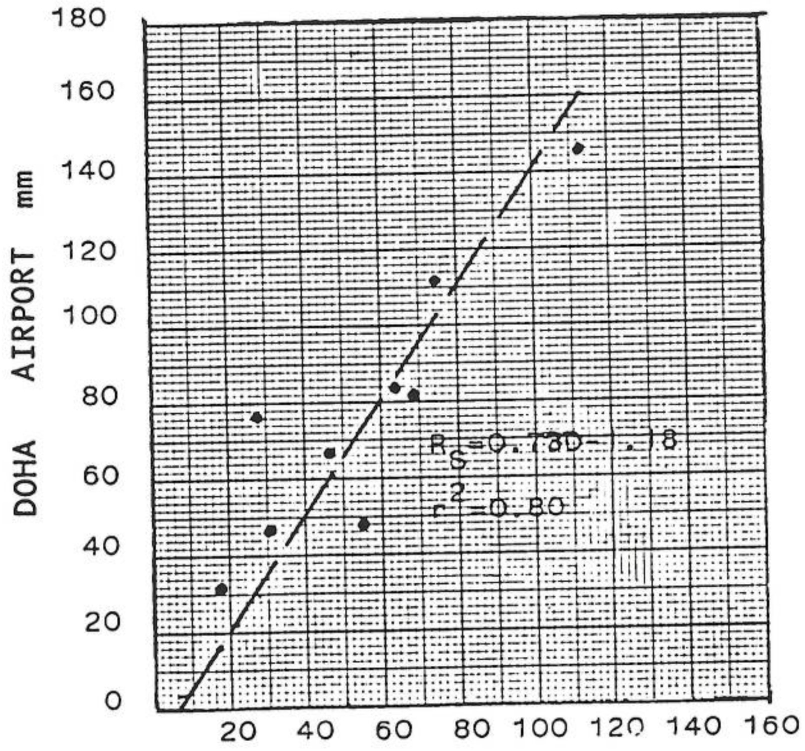


FAO Water Resources & Agricultural Development Project

MEAN ANNUAL RAINFALL
1971 – 1980



(A) NORTHERN QATAR



(B) SOUTHERN QATAR

RELATIONSHIP BETWEEN ANNUAL RAINFALL AT DOHA AIRPORT AND AVERAGE DEPTH OF RAINFALL OVER NORTHERN AND SOUTHERN QATAR

Fig. 5.9

Table 5.10

AVERAGE RAINFALL 1971/72 -' 1979/80

STATION	1971/72	1972/73	1973/74	1974/75	1975/'76	1976/77	1977/78	1978/79	1979/80	Total	Average
Ruwais	25.8	10.4	29.0	62.0	206.0	125.4	23.0	36.6	111.6	629.8	70.0
Govt. Farm	144.2	17.9	50.1	65.8	194.0	175.6	24.2	72.6	94.4	838.8	93.2
Alsafariyat	-	-	29.5	39.5	119.0	112.8	20.8	83.6	99.7	504.9	72.1
Alnasraniyah	36.7	21.2	60.3	81.6	97.0	92.2	28.4	-	85.0	502.4	62.8
Ummbab	16.6	18.4	22.5	38.3	84.0	57.0	17.8	58.6	73.6	386.8	43.0
Mile 32	25.0	-	16.1	40.1	120.0	90.0	27.6	49.6	68.6	431.0	54.6
Decca	-	-	59.2	123.5	129.0	94.5	29.4	42.4	67.8	545.8	78.0
Algamiliyah	-	-	-	-	-	41.6	37.4	59.2	27.6	165.8	41.5
Umm Saied	56.2	24.0	62.8	73.3	-	77.0	23.8	59.5	66.0	442.6	55.3
Karaanah	48.4	43.3	52.9	81.1	111.0	91.8	43.4	39.3	61.8	573	63.7
Khararah	21.1	20.1	65.2	53.7	116.0	54.4	22.2	92.8	59.2	504.7	56.7
Alaamiriyah	42.4	16.7	92.2	70.4	117.0	57.0	17.8	27.6	64.6	505.7	56.2
Trainah	38.6	18.0	100.0	42.5	137.0	59.6	24.6	19.6	53.9	493.8	54.8
Abu Samrah	-	-	-	-	114.0	26.8	30.2	32.4	54.4	257.8	51.6
Sauda Nathil	-	-	-	-	-	-	17.8	19.2	69.6	106.6	35.5
Umm Sikah	60.9	8.6	63.7	74.2	221.0	96.0	22.5	62.8	78.0	687.7	76.4
Wady Alwasaah	-	-	37.9	70.8	137.0	69.0	48.8	116.5	90.7	570.7	81.5
Alwobarah P20	-	-	-	-	-	55.2	47.5	72.6	41.4	216.7	54.1
Umm Alghap	-	-	-	-	-	71.4	26.5	35.0	45.8	178.7	44.6
Albombarah P22	-	-	-	-	-	100.8	-	51.4	24.6	176.8	58.9
Almagidah	44.2	28.5	50.5	63.3	194.0	196.4	22.0	52.7	97.2	748.8	83.2
ITDC Farm	-	-	-	-	-	98.3	27.1	80.2	96.4	302.0	75.5
Umm Alshokhot	-	-	62.5	52.4	106.0	77.5	34.9	24.3	77.4	436.0	62.3
Alwaikair	-	-	56.7	48.7	117.0	85.9	26.4	59.8	70.6	465.1	66.4
Dokhan	17.8	13.0	26.5	19.1	124.0	72.5	14.2	76.1	68.6	431.8	48.0
Umm Alafaie	-	-	49.2	59.2	119.0	92.2	52.3	93.7	72.2	537.8	76.8
Umm Almawagie	-	-	98.9	107.2	136.0	68.5	21.0	42.5	63.6	537.7	76.8
Siliyah	19.8	20.6	49.4	15.5	119.0	113.4	28.1	39.6	75.5	480.9	53.4
Doha Airport	39.7	30.8	50.4	70.4	154.0	80.5	34.7	56.5	-	517	64.6

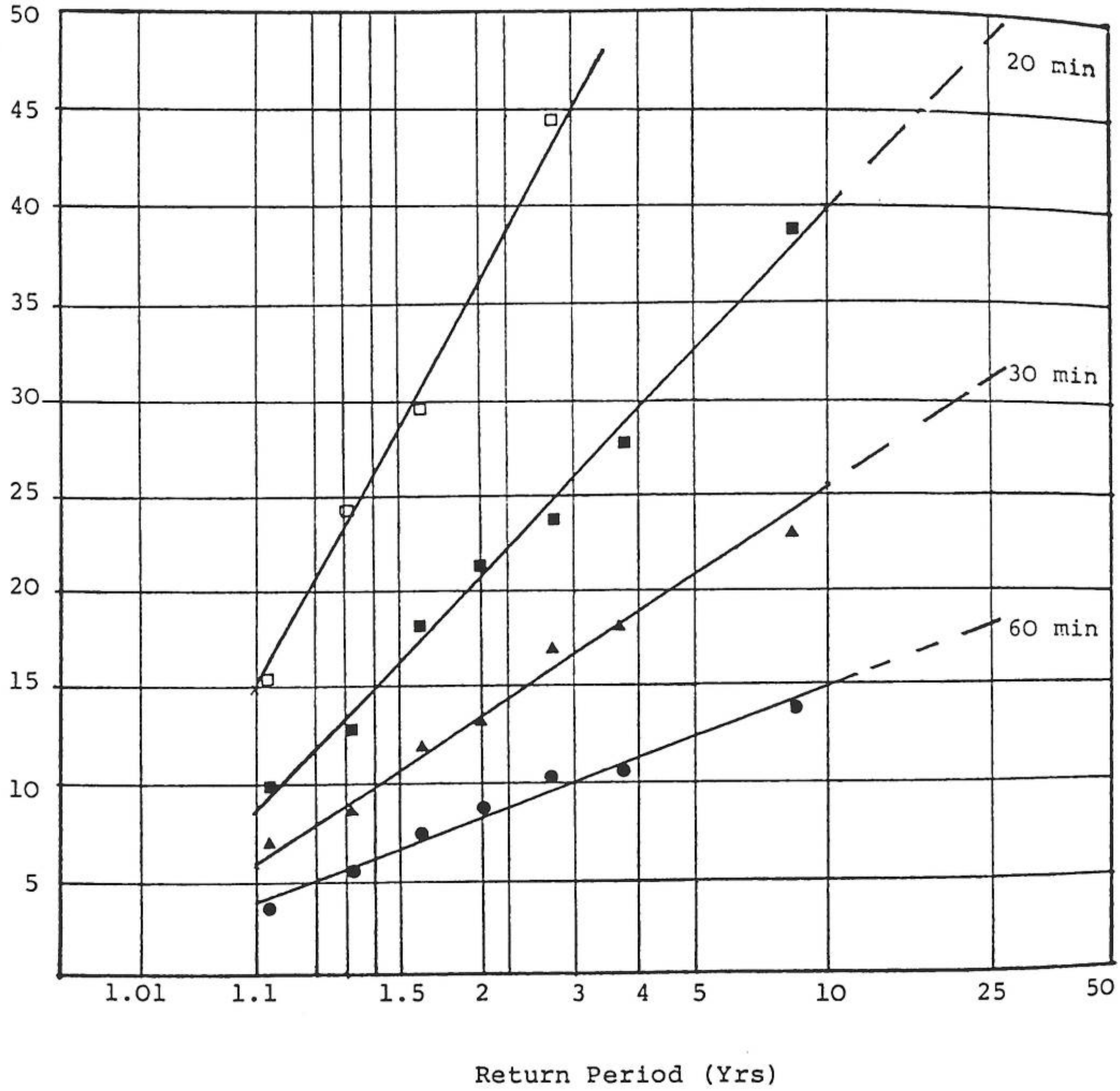


Fig. 5.10 RAINFALL INTENSITY RETURN PERIODS

Composite Data from autographic rainfall recorders at Rawdat al Faras, Abu Nkalah and Abu Samrah
1972 - 1979

Table 5.11

Mean Depth of Rainfall over Qatar

1972 - 80

(mm)

Year	Mean Depth of Rainfall			Maximum Recorded point Rainfall	Doha Airport
	North	South	Total Qatar		
1971/72	49.9	27.4	37.0	144.2	76.0
1972/73	17.8	18.6	18.2	43.3	31.1
1973/74	42.9	54.9	49.9	100.0	47.6
1974/75	58.4	63.6	61.4	123.5	84.6
1975/76	132.4	113.5	121.3	221.0	146.9
1976/77	114.1	75.0	91.7	175.6	113.0
1977/78	32.8	52.2	31.2	52.0	47.2
1978/79	59.5	46.3	51.9	116.0	66.4
1979/80	68.5	68.2	64.7	111.6	81.8

From the above data linear regressions of annual rainfall depth over Qatar on rainfall recorded at Doha airport have been developed for use in extending the time series of recharge. These regressions are also shown in Fig. 5.9 (a and b) and are;

$$R_N = 1.01\ D + 13.69 \qquad \text{.......... (5.1)}$$

$$r^2 = 0.94$$

and

$$R_s = 0.73\ D - 1.18 \qquad \text{.......... (5.2)}$$

$$r^2 = 0.80$$

where R_N = Mean depth of annual rainfall over northern Qatar

R_s = Mean depth of annual rainfall over southern Qatar

D = Annual rainfall at Doha airport.

5.8.4 Rainfall Intensity

Rainfall intensity data are of importance in developing rainfall/run-off-recharge relationships (Chapter VI) and data on point rainfall intensity has been obtained at ten autographic raingauges operated by the Project. However, at only three of these stations is the record sufficiently long enough to justify an analysis and even then the relatively short period of seven to nine years of record would only provide provisional rainfall intensity data which should not be extrapolated with confidence for much longer than the record itself.

Fig. 5.10 shows frequency plots of rainfall intensity in mm/hour of increasing durations upto one hour and for return periods of up to 10 years. These plots may be expressed in a generalised form as :-

$$I = \frac{92\ R^{0.38}}{D^{0.61}}$$

where

I = Intensity in mm/hr.

R = Return Period (yrs).

D = Duration (minutes).

In general, rainfall intensities are somewhat higher than those recorded elsewhere in eastern Arabia. For instance, in April 1972, 67 mm fell within an hour and a half at Rawdat al Faras and in December 1963, over 150 was recorded at Doha over a period of 3 days. The former was derived from a high intensity convective type thunderstorm with a limited area of fall and the latter was thought to be the result of a trough disturbance.

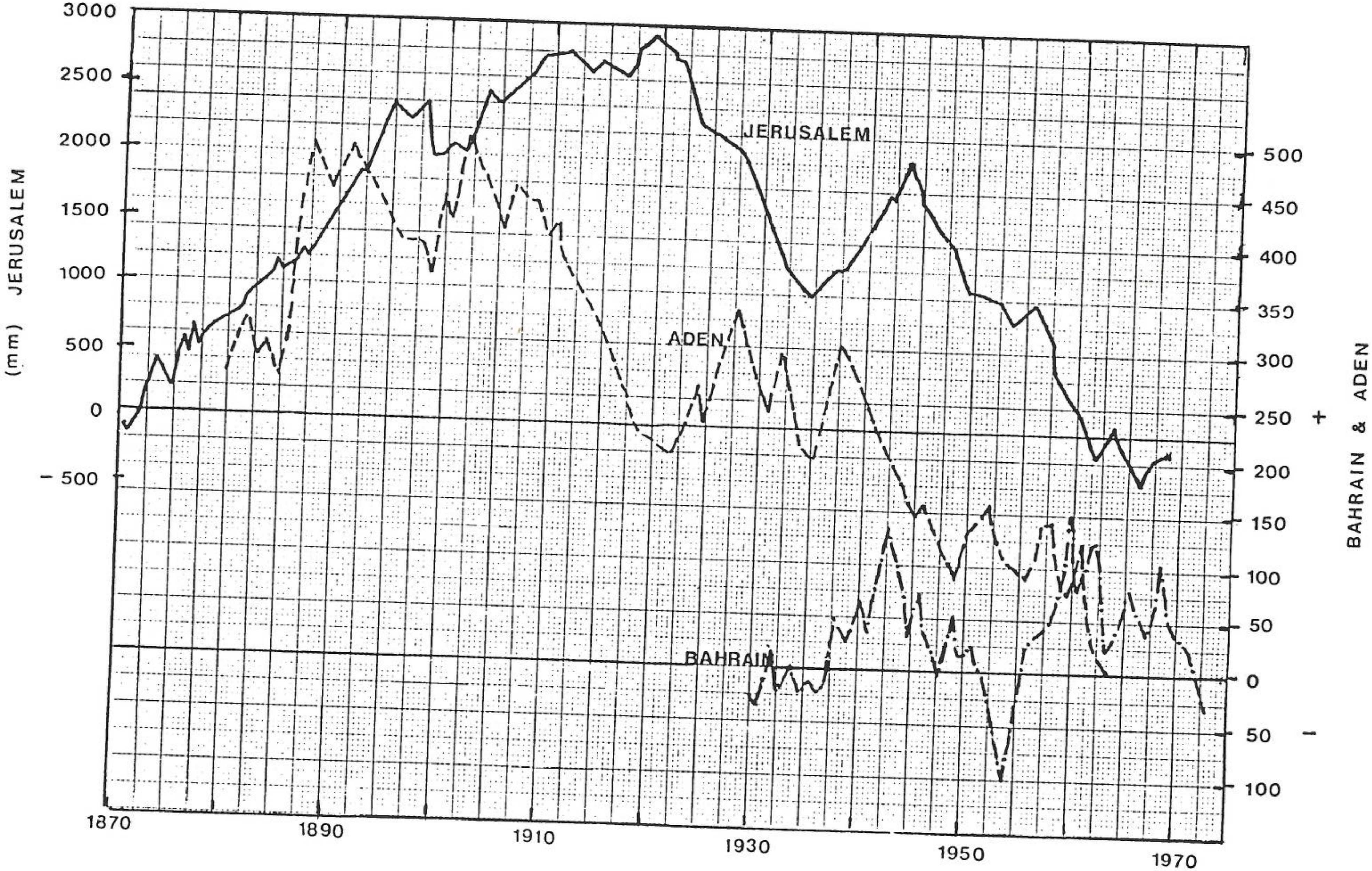
5.8.5 Secular Changes in Rainfall

The question of secular change in rainfall has occupied the attention of meteorologist and others for many years and is a subject of some controversy. Whilst many changes, particularly of an apparent cyclic nature, have been detected, none of these have been shown to continue for any length of time. There have also been many assertions that long-term changes in rainfall are responsible for changes in vegetation pattern and on the other hand archealogical evidence points to continued occupation of some sites in Arabia over the past four thousand years where the irrigated area has remained constant (cf. Raikes, 1968). There is however some confusion between cause and effect in many of the case studies cited, and the present and past situation in the large oasis area of Hofuf in Saudi Arabia and the prevailing situation in Qatar provides a relevant example.

In Hofuf evidence points to continued human occupation for at least four millenia with very little variation in the irrigated area, based as it is on the flow of a number of springs that have a present day discharge of about 10 m^3/sec. Thus, variations in rainfall over a protracted period would have had little effect on the irrigated area as the springs themselves are derived from an extensive aquifer system with a very large storage which was recharged during a prehistoric pluvial where marginal variations in historic rainfall and recharge would tend to be masked. In Qatar, however, groundwater occurs as a relatively small floating lens type aquifer, confined to the northern part of the peninsula and which has become established over a long time from direct rainfall. As the average rainfall is comparatively low only a slight variation in the long term rainfall would have disproportionate effect on recharge to this lens-type aquifer and, in this case, the secular changes in rainfall and hence recharge are of considerable importance in the long-term safe yield of the aquifer.

Fig. 5.11 shows a plot of cumulative departures from the mean annual rainfall at Jerusalem, Aden and Bahrain, for varying periods since the beginning of this century. All these records exhibit the well-known Hurst phenonmena (Hurst, 1957) and the record of Jerusalem and Aden show a mean value of K (as defined by Hurst) similar to that found for Nile discharges. The Bahrain record, although of much shorter duration, is however of importance in evaluating changes in rainfall and recharge in Qatar. It will be noted that from 1935 to 1952 there was an overall decline in annual rainfall followed by another 20 year period during which rainfall increased by one third. By relating the 18 year record at Doha to total rainfall and recharge over Qatar (see Chapter VI), it is noted that since 1962 there have been three separate trends in recharge calculated from rainfall/recharge relationships. From 1962 to 1968 average recharge is estimated to have been 36.4 x $10^6 m^3$ per annum but from that year to 1974 declined to a mean annual total of 11 x $10^6 m^3$, thereafter recovering to an annual average value of 31 x $10^6 m^3$. Thus it is clear that secular changes of rainfall, either in the long-term or in the form of shorter periods of 'persistence' of wet and dry years exert an important quantitative effect on the relatively small recharge area.

In an attempt to perhaps explain these short term fluctuations and provide a means of predicting them in the future, a relationship between the rate of change of sunspots and rain fall at Sharjah in the United Arab Emirates has been put forward by Halcrow (1969). The apparent. analogy between sunspots and rainfall has been propounded and investigated for many years, particularly in Central Africa where Brooks (1923) and Dixey (1924) demonstrated an apparent relationship between sunspot numbers and the then short record of levels of Lake Victoria and Nyasa respectively. Cochrane (1957) later extended this investigation and showed a much improved relationship by using the rate of change , instead of values of sunspot numbers, and lake levels, Pike (1965) later extended this work further by postulating a possible physical explanation of this phenomena by relating astronomical data with the distribution and



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changes in sea level pressure in the middle latitudes, its effects on the movement of the inter tropical convergence zone and hence rainfall and lake levels in central Africa.

A comparison between the three-year rate of change of sunspot numbers against three-year moving averages of rainfall at Bahrain and Sharjah and Doha was made and it is clear that while there is concordance between rainfall and rate of change of sunspots during certain cycles this is by no means persistent and indeed, the period of low sunspot activity between 1935-1945 corresponds to a period of above average rainfall at Bahrain and Sharjah. It is concluded therefore that despite claims to the contrary, the sunspot/rainfall analogy cannot be applied with any certainity as a means of predicting cycles of a high and low rainfall in the region. The Arabian peninsula lies outside the northern limit of the intertropical convergence zone and the relationship may well only hold true for tropical regions. The somewhat imprecise relationship between rainfall at Sharjah and sunspots put forward by Halcrow may perhaps be partly explained by the fact that this station lies on the boundary of the extreme northern limit of the inter-tropical convergence zone with some rainfall occuring during the summer.

5.8.6 Palaeoclimate and Recharge

The main freshwater aquifers of Qatar are those derived from recent recharge to the Tertiary sequence although it has been suggested that supplies of good quality water may be tapped in the Mesozoic and lower Paleogene formations. Deep drilling has already disproved this but at the same time there are valid palaeoclimatic reasons why such groundwater is likely to be highly saline, having been recharged during Pleistocene pluvial periods and because of the considerable distance to the main outcrop areas in central Saudi Arabia.

The extension of the European ice-sheets during the Pleistocene is deduced from characteristic erosional features and from types of morainic material directly attributable to the action of moving glacier ice. The number, sequence and approximate age of the four main climatic phases have long been accepted with confidence north of, say 40^{o} latitude, but less so in the periglacial regions and particularly the Middle East. The extension of an absolute chronology to zones other than the northern temperate zone encounters many difficulties; among them being differences in climate,absence of morainic evidence,relative scarcity of observations and lack of knowledge on the precise meteorological effects in the region brought about by glaciation in higher latitudes. Nevertheless, in a general way it is usually agreed that the path of rain-pearing maritime air masses which at present pass over western Europe would have been shifted southward by an area of high pressure over the ice-sheets. The evidence for increased rainfall or 'pluvials' in the Middle East during these glacial periods is fragmentary and inconclusive but Zeuner (1945, 1959) has adduced sufficient evidence to show that during the last glaciation, at least, three pluvial phases occurred. These are correlated with the advance, maximum extent and retreat of the ice sheet and have been tentatively assigned median dates of about 116,000, 72,000 and 22,000 years BP.

Environmental isotope sampling by the Project have provided ^{14}C dates of groundwater from the Umm er Radhuma and Mesozoic aquifers on south western Qatar, details of which are given in Chapter IX. Additional evidence in the form of ^{14}C dating of fossil lake beds at six separate locations in the interior of the Rub el Khali of Saudi Arabia (McClure, 1976) places the first period of deposition as being 36,000 and 17,000 years BP, with the concentration of dates between 9,000 and 6,000 years BP. Isotopic data and radiocarbon dating of the waters of the deeper aquifers of eastern Arabia point to a period of major recharge during Zeuner's third or Würm pluvial period (22,000 years BP) with additional substantial recharge during later wet phases at the beginning of the historical era between 9,000-6,000 years BP and intermittently into modern times.

VI

HYDROLOGY

6.1 INTRODUCTION

Direct and indirect recharge from rainfall to groundwater is the sole natural water resource of Qatar and quantitative estimates of its magnitude and frequency are of fundamental importance to any assessment of available groundwater resources and their optimum development. In this chapter quantitative estimates of surface run-off and recharge based on field observations and surveys carried out between 1972-79 are presented. This estimate is supported by hydrochemical and environmental isotope data presented in Chapter VIII.

A review of the basic recharge processes as observed in Qatar has been given in a previous report (FAO, 1974) and it is not necessary to repeat them here. In summary, recharge over Qatar may occur directly as infiltration of rain falling on the outcrop of the aquifer, or indirectly by infiltration of run-off to wadi beds and from run-off accumulated or ponded in terminal depressions. The quantitative determination of direct recharge to outcrop has proved to be intractable and that to pervious material necessarily imprecise owing to the wide difference in infiltration rates between different soil types. The determination of indirect recharge from ponded terminal run-off as a residual after evaporation, soil moisture and other losses have been accounted for is, however, more amenable to quantitative assessment and a certain amount of data has been accumulated by the Project on this indirect process, which accounts for the greater proportion of recharge over Qatar.

A major proportion of the land surface of Qatar is made up of some 850 contiguous depressions of interior drainage with catchments varying in extent from 0.25 to 45 km^2. These depressions are the result of the solution of gypsum and anhydrites in the Rus Formation, or the development of sub-surface caverns resulting from karstification of the calcareous facies of the same formation, and the subsequent collapse of the roof whose surface expression is a general subsidence. A large number of these depressions are approximately circular in outline with the floor a few meters to 20 meters below the surrounding erosion surface, with colluvial calcareous and sandy soils covering the floor of the depression to a depths of up to 1.5 m.

In northern Qatar these depressions are generally shallow and saucer-like in cross-section with the colluvial *roda* soil reaching its maximum depth in the centre. After moderate to heavy rainfall run-off from the surrounding bare litholosol catchment reaches these depressions by a number of incipient drainage channels or wadis or directly by sheet overland flow. After heavy storms the depth of ponded water may be as much as 0.5 meter and remain on the surface for a considerable length of time.

Earlier investigators assumed that recharge to the sub-out-crop was the residual in an equation which accounted for soil moisture storage, evaporation and direct rainfall on the ponded area. While field evidence seemed to support this view, later concurrent observations of well levels and soil moisture at depth pointed to the probability that recharge was only taking place around the margin of depressions where the soils are shallow and quickly saturated, and also where the maximum extent of fracturing associated with the collapse of the depression was likely to be found. The visible pond in the middle of a *roda* soil depression, still apparent a weeks or so after rainfall, was found to be perched over a soil sometimes only saturated for part of its profile. Field surveys of declining water levels after ponding have confirmed an exponential type decline in water level and thus indicating fairly rapid initial rates of infiltration and/or recharge.

In central and southern Qatar the depressions are more crater-like in appearance with a floor sometimes as much as 20 meters below the general land surface and covered with a mantle of aeolian sand of varying depth. In many of these depressions the deeper sands support a sometimes dense growth of *Acacia-Ziziphus-Lycium* surviving on soil moisture storage, thus suggesting that recharge to the sub-outcrop is considerably reduced. The differences in morphology between the two typical types of depression and their hydrogeological significance is discussed more fully in Section 6.4.1.

6.2 SURFACE RUN-OFF

Earlier data on run-off to depressions and consequent infiltration and recharge have been infrequent and the results generalised. Legrand Asco (1959) estimated that between 10-15% of rainfall above 12 mm day^{-1} reached the depressions as run-off where 70% was infiltrated and 30% evaporated, indicating an infiltration of 7-10% which was assumed to be recharge. Pencol (1965) concluded, however, that infiltration and recharge from depression storage was considerably greater. This estimate was based on extraction data from Water Department well-fields from which they concluded that recharge lay in the range 15-22% of the rainfall.

On 19 April 1972 a heavy thunderstorm was centred over Rawdat al Faras (Government Farm) from which 67.6 mm of rain fell in 90 minutes and flooded area of 0.72 km^2 from a catchment of 10.4 km^2, giving a run-off of 26% of rainfall (see Table 6.1). From observations of declining water levels and allowing for evaporation of ponded water and soil moisture storage, the resulting recharge was calculated to have been 20% of rainfall, confirmed by an analysis of the growth and decay of the groundwater mound below the depression area. In 1975, additional observations were made in the vicinity of Karanah in south-central Qatar which indicated a run-off of 18% of rainfall.

Arising out this work it became clear that the run-off-infiltration-recharge mechanism was more complex than hitherto assumed and the wide application of coefficients derived from a few isolated observations could prove to be misleading. With the assistance of an FAO hydrometrist on a short-term assignment a comprehensive field programme of observations on run-off and infiltration was therefore undertaken during February/March 1976, which fortuitiously proved to be a period of higher than average rainfall. During this period some 30 observations of infiltration from ponded flood water and 12 observations of rainfall, run-off and infiltration to depressions were carried out (Gemmell, 1976). This work consisted of evaluating rainfall data over the catchment, frequent observations of falling ponded water levels, discharge observations of flow between adjacent depressions and a topographic survey of the entire flooded area of the depression after the waters had receded.

In January and March 1979 widespread rain fell over Qatar in two separate and distinct storms with widespread flooding of depressions. While the observations of 1976 were complicated by prolonged rainfall contributing additional unknown quantities of run-off to already flooded depressions, the events of 1979 provided valuable data from entirely separate and unrelated events. A further six flooded depressions were surveyed from which run-off, evaporation and infiltration volumes were determined.

All these data are summarised in Table 6.1 which shows the very wide variation in deduced run-off and infiltration, varying from 8% to 86% in the case of the former and 6.8% to 94% in the case of the latter. Clearly the higher values are nonsensical and point to the need for a very high degree of accuracy in the determination of rainfall and the storage volume where both are very small. For instance an error of 1 mm in rainfall on the small catchments will result in an error of 5% in the calculated run-off percentage and this fact is largely responsible for the wide scatter of results. It was impracticable to determine the exact amount of rainfall on each of the smaller catchments, some as small as 0.4 km^2.

By combining the 1979 data with that of earlier observations on a selective basis and omitting observations on small catchments for which there were no reliable rainfall data or complicated by additional rainfall, Harhash (<u>Rainfall-Run-off-Recharge-Evaluation - Qatar</u>

TABLE 6.1

SUMMARY OF RAINFALL - RUN-OFF - RECHARGE OBSERVATIONS

1972 - 1979.

Location	Date	Catchment Area km^2	RAINFALL		RUN-OFF		LOSSES				RECHARGE		
			mm	$m^3 \times 10^3$	$m^3 \times 10^3$	%	Evap. $m^3 \times 10^3$	Soil Moist $m^3 \times 10^3$	Total $m^3 \times 10^3$	% of Run-off	VOL. $m^3 \times 10^3$	% OF RUN-OFF	% OF RAINFALL
Govt. Farm	19.4.72	10.40	67.6	700.00	200.00	28.5	7.200	20.00	27.20	13.6	172.80	86.4	24.7
Recharge W. N	23.2.76	0.23	31.0	7.13	3.79	53.0	0.109	9.22	11.03	27.2	2.76	72.8	38.7
" " C	"	1.08	31.0	32.64	7.07	21.6	0.146	1.34	1.49	20.7	5.58	80.0	17.1
" " S	"	0.40	31.0	12.40	9.69	78.1	0.271	1.64	1.61	16.6	8.08	83.4	65.2
" " S	29.2.76	0.40	31.0	2.34	0.24	11.0	0.006	1.64	1.65	-	-	-	-
Dandia	23.2.76	1.90	31.0	58.90	17.34	29.4	1.634	5.76	7.39	42.6	9.94	57.3	16.9
Dep. C	5.2.76	1.75	16.5	28.87	6.64	23.0	0.501	7.20	-	100	-	-	-
" "	12.2.76	1.75	12.7	22.22	1.92	8.6	0.453	7.80	-	100	-	-	-
" "	22.2.76	1.75	31.5	55.12	25.96	47.0	2.419	7.20	9.62	37.0	16.34	63.0	29.6
Al-Ghouriah	5.2.76	28.75	10.0	282.06	50.80	18.0	4.064	3.20	7.26	14.3	43.54	85.7	15.4
"	12.2.76	28.75	10.0	281.09	22.67	8.0	2.630	21.60	24.23	100	-	-	-
"	23.2.76	28.75	26.0	722.79	75.41	10.4	4.373	21.60	25.97	34.4	49.43	65.6	6.8
Al-Otoriya	13.3.79	1.75	38.4	67.20	14.96	22.3	0.974	4.89	5.86	39.2	9.09	60.8	13.5
Umm Alfai	13.3.79	0.37	73.5	27.56	6.84	24.8	0.231	2.05	2.28	33.3	4.56	66.7	16.6
K33 (South)	13.3.79	0.99	91.5	90.58	20.54	22.7	1.877	5.82	7.70	37.5	12.83	62.5	14.2
K33 (North)	13.3.79	0.36	91.5	32.94	6.34	19.3	0.235	1.78	2.02	31.8	4.33	68.2	13.1
P22 Well	13.3.79	0.49	38.4	18.74	3.52	18.8	0.357	3.79	4.15	100	-	-	-
Wadi Al-Wassa	13.3.79	1.08	91.5	98.82	15.62	15.8	0.820	7.41	8.23	52.7	7.39	47.3	7.5

(1971/72 - 1978/79), Project Technical Note No. 7, 1980) developed a series of multiple regression equations for run-off and recharge with rainfall duration amount and catchment area as independent variables.

These are :

For run-off :

$$R_o = 188 \left[(6.5 + h) + 8T \right] A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

and recharge

$$R_c = 124 \left[(12 + h) - 3T \right] A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where R_o = Run-off volume in $m^3 km^{-2}$

R_c = Recharge volume in $m^3 km^{-2}$

h = Rainfall in mm

R = Storm duration in minute

A = Catchment area in km^2

The multiple correlation coefficient in the case of equation (3) is 0.8456 and somewhat less for equation (4) although both would be expected to improve with additional data. Pending refinement, the equation should however be used with caution and noting also that equation (4) refers to indirect recharge from ponded run-off only and does not take into account additional recharge from wadi bed or direct infiltration.

Run-off is dependent upon catchment size and shape but rainfall amount, duration, intensity and distribution over the catchment are of critical importance. Run-off generally occurs only after 8 to 10 mm of rain has fallen, provided soil moisture has been brought to near field capacity or the upper surface layer saturated by antecedent rainfall. In many cases initial storms of 10 mm have failed to produce run-off. Rainfall distribution over the catchment appears, however, to exert a greater effect on run-off than the total fall. This is clearly shown by the events of 5 and 12 February 1976 in the Ghuwairayah catchments. Both storm events produced a mean fall of 19 mm over the catchment but the resultant run-offs were 18% and 8% respectively. The storm of 13th February was the heavier with a mean fall of 13 mm in the vicinity of the depressions with less rainfall towards the boundary of the catchment. On the other hand the storm of 12th February was evenly distributed across the catchment with an average fall of 10 mm and despite the fact that antecedent soil moisture conditions were more favourable for run-off, this amounted to less than half that produced by the earlier storm.

On the assumption that these exteremely variable rates of run-off from small catchments would tend to an average value in both space and time, the average mean weighted run-off rate indicated by direct Project investigations of some 19 separate events is 24.3%, and 22.6% from the sample used in deriving the regression equations.

6.3 INFILTRATION

As with run-off, infiltration of ponded run-off in depressions exhibits a wide observed variation from 10% to 94% of total rainfall noting that this total also includes direct rainfall on the ponded area as ponding from direct rainfall occurs before, during the after run-off. In addition to observations of infiltration in the larger surveyed depressions, additional observations of water level decline in a wider sample of flooded depressions were obtained during the winter of 1976. These clearly show the importance of soil texture of the upper part and periphery of the depression is generally sandy with a coarse fraction and the infiltration rate was observed to be of the order of 3 to 4 mm/hr. In the larger terminal depressions, where the finer fractions of silt and clay have accumulated, the infiltration rate is reduced to between 0.05 to 1.5 mm/hr. The higher rates of infiltration observed on the margins of depressions is consistent with the hypotheses that recharge from ponded run-off takes place principally around the margin of a depression.

In the sand dune areas of southern Qatar, some of which overlie sub-outcrop of the Dammam formation and the terminal of the Alat aquifer, the infiltration rate is extremely high - of the order of 100 to 150 mm/hr.

6.4 RECHARGE

6.4.1 Recharge Area

Previous recharge estimates were based on a total recharge area of 6,500 km^2 being an estimate of the total internal drainage area of Qatar (FAO, 1974). With the provision of detailed topographical maps in 1974 a delineation of the water-sheds of some 850 depressions and their individual areas computed. In addition, areas of featureless desert were excluded from the active internal drainage area. This close delineation of the internal drainage system was then grouped into ten separate sub-basins and which subsequently formed the basis of a detailed recharge estimations. This delineation and sub-division of the total area of Qatar resulted in the following :

Total aggregate internal drainage area	=	7,225 km^2
Total aggregate internal non-drained area	=	2,007 "
Total external drainage area	=	2,378 "
Total	=	11,610 "

With the accumulation of additional hydrogeological data and the recognition of two separate hydro-geological provinces based on differentiation in limestone facies in the Rus Formation, the earlier sub-division of recharge areas was discarded in favour of a simpli-fied division between the northern and southern regions of the country. The boundary between these two provinces is a V-shaped one, first identified by the Project geophysical survey, as a discontinuity between a moderately resistive formation to the north and a more highly resistive one to the south. Subsequent field geological investigations have revealed a carp feature in the 'apex' area of the boundary (Fig.3.13) coincident with this geophysical boundary (see Chapter III). Exploratory drilling has also confirmed the predominant carbonate facies of the Rus Formation of northern Qatar where gypsum has largely been removed y dissolution, leaving a characteristic deflated landscape. In this province the absence f lower Dammam shales is significant factor whereby recharge has gained access to the Rus Formation whereas in southern Qatar their presence has undoubtedly reduced recharge except ı a number of isolated areas. These latter are characterised by a pronounced depression, ometimes as much as 20 meters below the general surface, and have probably formed where gypsum in the Rus Formation has been removed as a result of fracturing caused by the dolomi-ization process affecting the Dammam Formation which has allowed meteoric waters to preco-ite downwards. Fig. 3.12 illustrates the different geological structure of each of the two main types of depression.

Based on these hydro-geological arguments and supported by field data, a re-distri-bution of the total area of Qatar into effective recharge areas has been made. In the southern area this includes only those areas where pronounced depression features occur - u Nakhalah, Mukeynis, Al-Matkhiyah, Karn'ah, Al-Amiriyah, At-Turayna, Al Ghashem and ..ere hydrochemical evidence has indicated the presence of a recharge component in ground-water (see Chapter IX). This has resulted in a re-distribution of the total area of Qatar to the following categories and which have been adopted for the estimation of recharge.

		North	South
Total aggregate area of internal catchments	=	3168	4057
Total aggregate of non-drained areas	=	695	1312
		3863	5369

Direct recharge over the external catchment area is assumed to be ineffective as it would be rapidly taken up in saline groundwater or on sabkha.

6.4.2 Recharge Estimates

As noted earlier, recharge to groundwater is by two main processes; a direct one resulting from prolonged rainfall over extensive areas of lithosols and bare outcrop and from accumulation in small hollows where soil depth is minimal and, secondly, by an indirect process from run-off to, and subsequent infiltration through, the colluvial soils of the 850 depressions of Qatar. In the case of the former, data is extremely difficult to obtain but a simplified model of rainfall data, evaporation rates indicates that approximately 3% of accumulated storm rainfall above 10 mm day^{-1} or 2% of the annual rainfall may be directly recharged to the northern calcareous facies of the Rus Formation. The presence of the Dammam Formation Shales in western and southern Qatar would seem to preclude any possibility of direct recharge.

In the case of indirect recharge resulting from run-off, ponding and infiltration in depressions a certain amount of data are available; but even here considerable variations have been found to occur and it is only possible to provide an estimate based on average data. In Table 6.1 the proportion of rainfall infiltrated after all losses are accounted for, ranges from Nil to 64.2% with a weighted mean of 15.0% as a percentage of storm rainfall or 10% of annual rainfall has been adopted. In southern Qatar this percentage has been reduced because of the more widespread areas of sand and vegetation in depressions. The extent of this ground cover is densest in those areas where the maximum amount of run-off accumulates and it is estimated that only 6% of annual rainfall may be indirectly recharged. The following table shows the adopted values upon which all subsequent calculations have been based.

Table 6.2

Areas and Recharge as a Percentage of Annual Rainfall

	Direct		Indirect	
	Area	%	Area	%
Northern	3863	2	3168	10
Southern	5369	–	4059	6

To provide a time series of recharge the relationship between the 18-year rainfall record at Doha airport and mean rainfall over northern and southern Qatar (see Page 5/28) was used to calculate the probable mean depth of rainfall over these areas and to which the derived recharge factors were applied. These data are shown in Table 6.3.

Cumulative departures from the mean value of annual recharge may be divided into three separate periods :

(1) 1962/63 to 1968/69 - Recharge 37% above average

(2) 1968/69 to 1974/75 - Recharge 59% below average

(3) 1974/75 to 1979/80 - Recharge 17% above average

While the record is insufficient long enough to discern any periodicity it is however clear that there is a certain tendency for the persistence of periods of up to 7 years during which time recharge may be above or below average by half an order of magnitude. Whilst storage is sufficient to overcome a 7 year below average recharge period at present pumping levels, water quality in marginal areas would expect to deteriorate rapidly under the same conditions.

Fig. 6.1 shows a probability plot of deduced annual recharge in northern Qatar against various computed return periods (Gumbel). As the data were originally derived from rainfall data, the good fit is to be expected and does not indicate consistency in recharge observations. Nevertheless, it will be noted that the present extraction in northern Qatar ($38 \times 10^6 m^3$) is equivalent to a recharge return period of 4 years or in other words there is only a 25% chance that the extraction rate will be matched by an equivalent volume of recharge in any one year. Actual groundwater observations related to recharge events have been analysed by Harhash (1980) and are presented Chapter IX.

The estimation of recharge in desert areas presents an intractable problem and while a search of the literature reveals a considerable number of theoretical models which may be applied to the problem, very few are based on actual field data of rainfall, run-off, infiltration and recharge and are therefore uncertain. The Project therefore undertook to obtain the necessary data on the major recharge mechanism and the deduced recharge based on these data is considered to be close to actual conditions. The estimation of recharge by environmental isotopes is considered in Chap. IX.

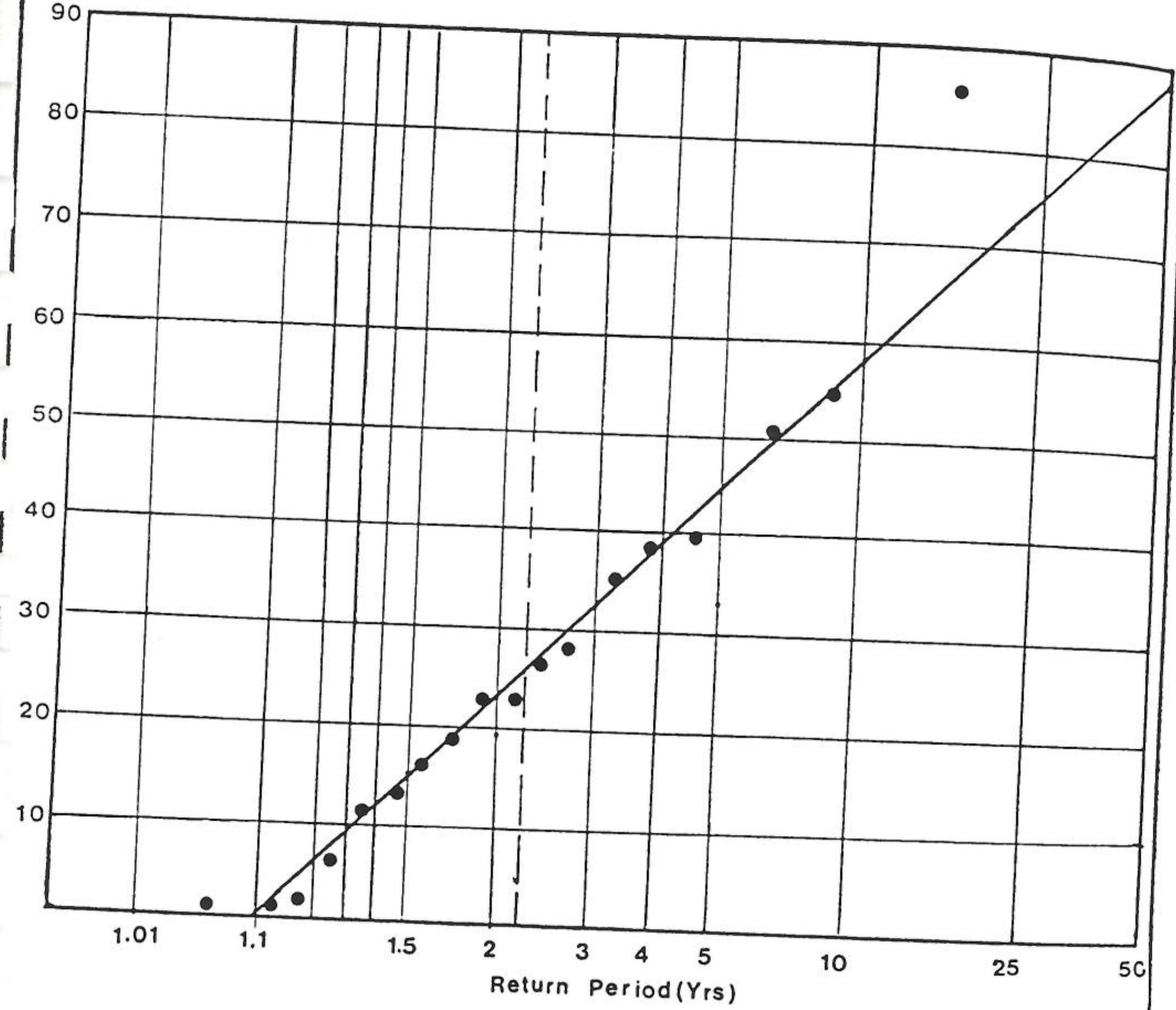


Fig 6.1 Return Period (yrs) of Annual Recharge in Mm^3
Northern Qatar

VII

GEOPHYSICAL SURVEYS

7.1 INTRODUCTION

Geophysical surveys have been carried out over Qatar and its offshore areas both in the exploration for oil and gas and in the search for an understanding of the groundwater resources. Seisimic and gravity surveys were made by the oil companies and the Qatar Petroleum Production Authority (onshore) and (Offshore) but their objectives were the deep Jurassic and Cretaceous formations and, though valuable to the understanding of the formations and the fundamental geological structure of Qatar, they do not contain much pertinant information on the regional and national hydrogeology. Similarly, the logging of exploratory and production oil and gas boreholes was not oriented to obtaining data from the upper layers and only occasional details were relevant to the shallow fresh and saline water aquifers.

Specifically in the search for groundwater, resistivity surveys were carried out by Le Grand Adsco (1959) Compagnia Mediterranea di Prospezioni (C.M.P.)(1972), Geotest (1976) on behalf of the Project, under subcontracts with F.A.O., and by IDTC/Geoterrex (1979).

Each of these surveys was made to identify variations in formation resistivity factors which could be interpreted to separate the fresh from brackish or saline ground water. With estimates of aquifer porosity, calculations of aquifer potential and groundwater reserves were also attempted.

Detailed surveys of depressions were also carried out to determine the variation in aquifer conditions between the collapsed and the surrounding area, to a degree that could be detected by resistivity methods, and thus delimit the nature and quantity of freshwater reserves.

7.2 SUMMARY OF SURVEY RESULTS

7.2.1 Le-Grand Adsco (1959)

The resistivity survey by Le Grand Adsco (1959) was oriented towards the location of freshwater reserves at shallow depth. Depth profiling was restricted to the major depressions and the survey was limited to northern Qatar only. Calculations of groundwater reserves, associated with the depressions catalogued, were based upon assumptions made for the Sinnah Wellfield. This area, near the centre of the peninsula, had been explored in the early 1950's for a source of potable water for the expanding activities of the Dukhan oilfield. Pumping started at the beginning of 1956 and at the time of the Le Grande Adsco survey, 3 to 4 years of data on groundwater extraction rates, levels and qualities were available together with rainfall amounts extrapolated from the records of Dukhan, some 40 km away to the west southwest. Based upon these data, presented in greater detail in Chapter IX of this Report, calculations of reserves at Sinnah were given and the same basic assumptions were extended to the remainder of the depression survey.

The results of this survey, a most valuable appraisal steady-state conditions of pre-development made 20 years ago before any major exploration of groundwater reserves and when the demands for potable water were rising rapidly, far outstripping the known sources and thus limiting the economic expansion and social development of the country, were based upon very limited control information and are thus of relative accuracy for a present-day appraisal of groundwater potential.

However, the basic multi-layer variable-parameter conditions were recognised and described as follows :

Surface layer	Generally dry sand, silt or clay, with high resistivity and small depth, except where saturated.
Dry rock above water table	May be of higher or lower resistivity than the surface layer depending upon the condition of the groundwater surface. Resistivity plots as a gradual increase or even an inflection with increasing depth in the case of a dry surface; or a maximum if the surface has a reduced resistivity due to moisture.
Rock below water table	The presence of water reduces the resistivity considerably and abruptly. Since the value of each point on a depth profile is a summation of the varying resistance to that depth, the effect of the abrupt boundary-decrease only appears on the curve as a gradual decrease. The effect of saline water below fresh is to increase the rate at which resistivity decreases with depth.

However, an inspection of the results obtained and the plotted curves, reveals that several of the possible combinations of conditions seem to occur together below the surface area of many of the depressions. The level of the water table is rarely indicated by a useable change of graph slope, and the abrupt change from fresh to saline water is not obvious.

The methods and interpretations used, backed by considerable amount of percussion well drilling and slim-hole deep drilling, did not reveal the extent of the freshwater reserves nor the depth to the base of the freshwater body. The freshwater zone was erroniously assumed to exist only above sea-level though a hint of the possibility of considerable sub-sea-level reserves was provided. The depth at which the quality of the recharged water approaches that of sea water is not known but is greater than 60 m below sea level beneath the Maidhir Depression (in the north central area), the largest in Qatar extending over 200 hectares.

7.2.2 C.M.P. (1972)

A sub-contract of the UNDP/FAO Hydro-agricultural Survey Project was awarded to the Compagnia Mediterranea di Prospezioni (CMP) in 1972 for an overall survey by electrical soundings, following the Project recommendation in December 1971. The survey was conducted to locate the freshwater aquifer in Qatar, to permit an estimate of the amounts of fresh groundwater available and to identify areas suitable for the further exploitations of groundwater reserves especially in the southern part of the peninsula.

The CMP survey made a total of 143 depth profiles (DP) and 19 lateral profiles (LP). The DPs were made using a Schlumberger electrode array with AB spacings varying from 600 m to 3000 m. 78 DPs were made along 6 traversed lines and 65 DP s were made in same 17 selected depressions. Nineteen LPs were made, generally with an AB separation of 400 m, (though one at 600 m and 7 at 200 m were also carried out), within the selected depressions.

The results of the survey were significant in that the division of the peninsula into two groundwater profinces was made apparent for the first time. In the <u>north</u> and <u>central</u> areas a three layer situation was described :

- a surface layer with high resistivity (200-1000 ohm.m.)
- an intermediate layer (30 - 100 ohm.m.)
- a conductive medium (0.3 - 30 ohm.m.)

The surface layer was related to dry surface rock, the intermediate layer to limestones containing the freshwater reserves, and the conductive medium to limestone containing the underlying saline groundwater. Fig. 7.1 is a composite plot, based upon several matching DPs, to show the overall conditions.

In the south, the situation was interpreted as follows :

- a surface layer with high resistivity 200-1000 ohm.m.
- an intermediate layer 10 - 120 ohm.m.
- a resistive medium 200 ohm.m.

The surface layer was again dry rock, the intermediate assigned to the aquifer zone nd the lower resistive zone was posed as compact dry rock. Fig. 7.2 gives details, again from several typical profiles.

Interpretation of the lateral and depth profiles was aided by the existence of Electrical Logs made by Schlumberger for the "superficial" (the upper 300 m) layers in early oil exploration boreholes. Details of these logs and their hydrogeological inter- etations are given later in 7.3.

Good evidence of the variation in thickness, particularly of the intermediate fresh- ter aquifer zone, permitted an appraisal of the general configuration of the freshwater body.

By selecting data from the appropriate AB dimension of 400 m, and 600 m corresponding an approximate depth penetrations of 200 m, and 300 m, isoresistivity maps were prepared from which it is clear that the intermediate resistivity zone, with an outline similar to t of the peninsula is restricted to the north and centre of the country. Fig. 7.3 and illustrate the findings.

A value of 3 ohm.m. was selected as indicative of the transition from the freshwater of intermediate layer to the saline water conditions of the conductive medium below and an appropriate contour map of the base of the freshwater body was drawn. This indicated the ral shape of the body with a deepest level of more than 100 m below sea level in the re of the peninsula rising to sea level at or near the coast. Enclosure 3 presents the details at a seate of 1:200,000.

Evidence of a separate narrow belt of the conductive medium beneath a zone of low resistivity was also interpreted as a south-western repetition of the northern condition ith potential for the exploitation of freshwater reserves. Elsewhere in the southern area presence of an extensive resistive medium was recorded with little prospect for useable dwater resources.

The CMP (1972) survey was limited in extent and density of DP and LP survey points and for northern Qatar was the overall pattern of lateral and vertical variation in esistivity sufficiently clear for firm interpretation. In addition, expert contractor held vations concerning several factors, particularly thickness changes within the inter- te layer, specially the lateral thinning of the freshwater body and the overall effect on the resistivity values assigned to the aquifer, the Umm er Radhuma and the overlying ormation, above the conductive medium in the north and the resistive medium in the True thicknesses were difficult to estimate due to the surface resistive layer reen effect and resistivity changes within the intermediate layer itself. In the south of relationship of an intermediate layer between two media of high resistivity presented onal problems of interpretation. No attempt was made to quantify the volume of fresh- er reserves by calculation of rock volume dimensions and estimates of porosity and nsmissivity.

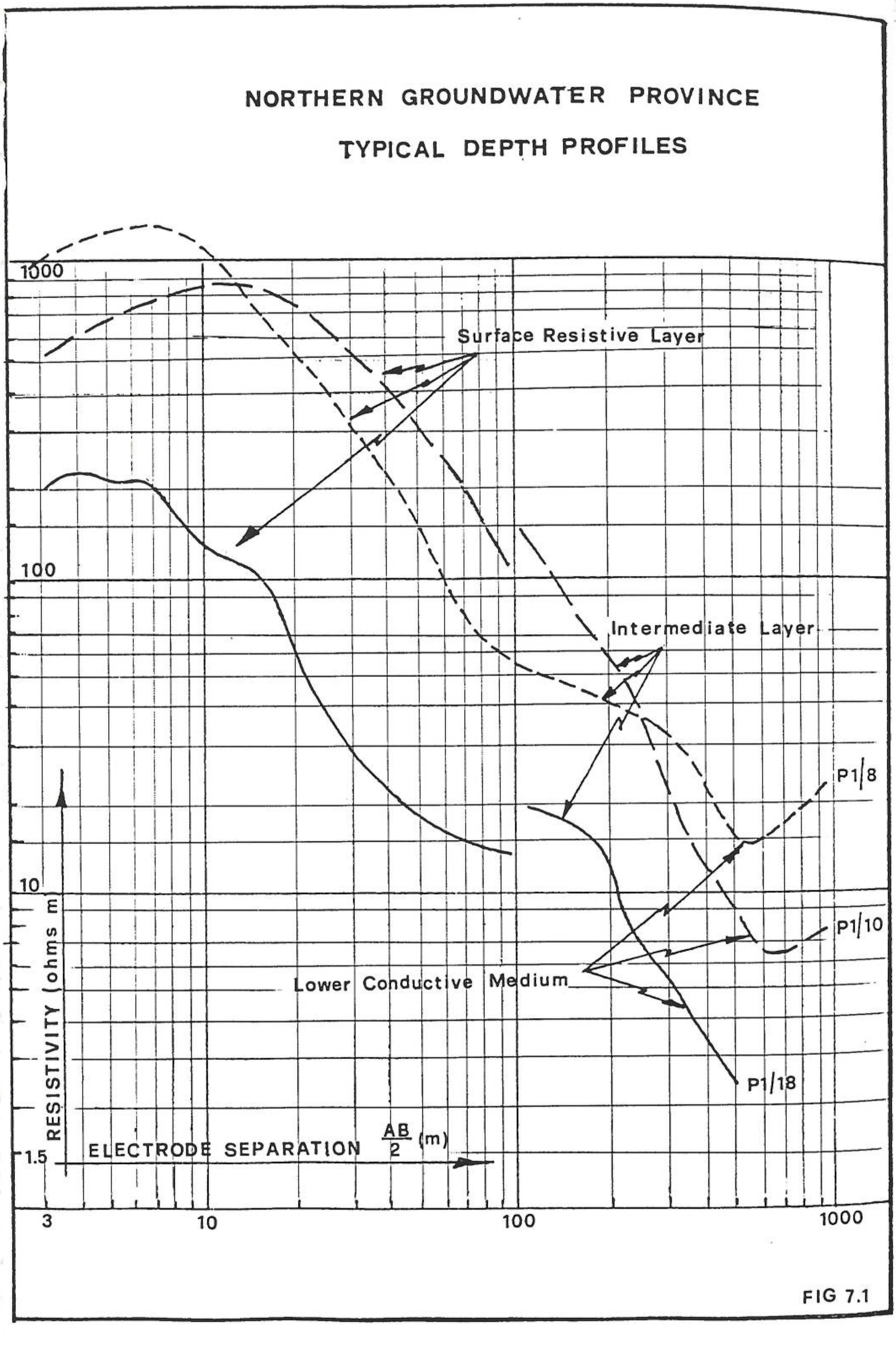

NORTHERN GROUNDWATER PROVINCE
TYPICAL DEPTH PROFILES
1000
100
10
1.5
Surface Resistive Layer
Intermediate Layer
Lower Conductive Medium
P1/8
P1/10
P1/18
RESISTIVITY (ohms m)
ELECTRODE SEPARATION AB/2 (m)
3
10
100
1000

FIG 7.1

SOUTHERN GROUNDWATER PROVINCE
TYPICAL DEPTH PROFILES

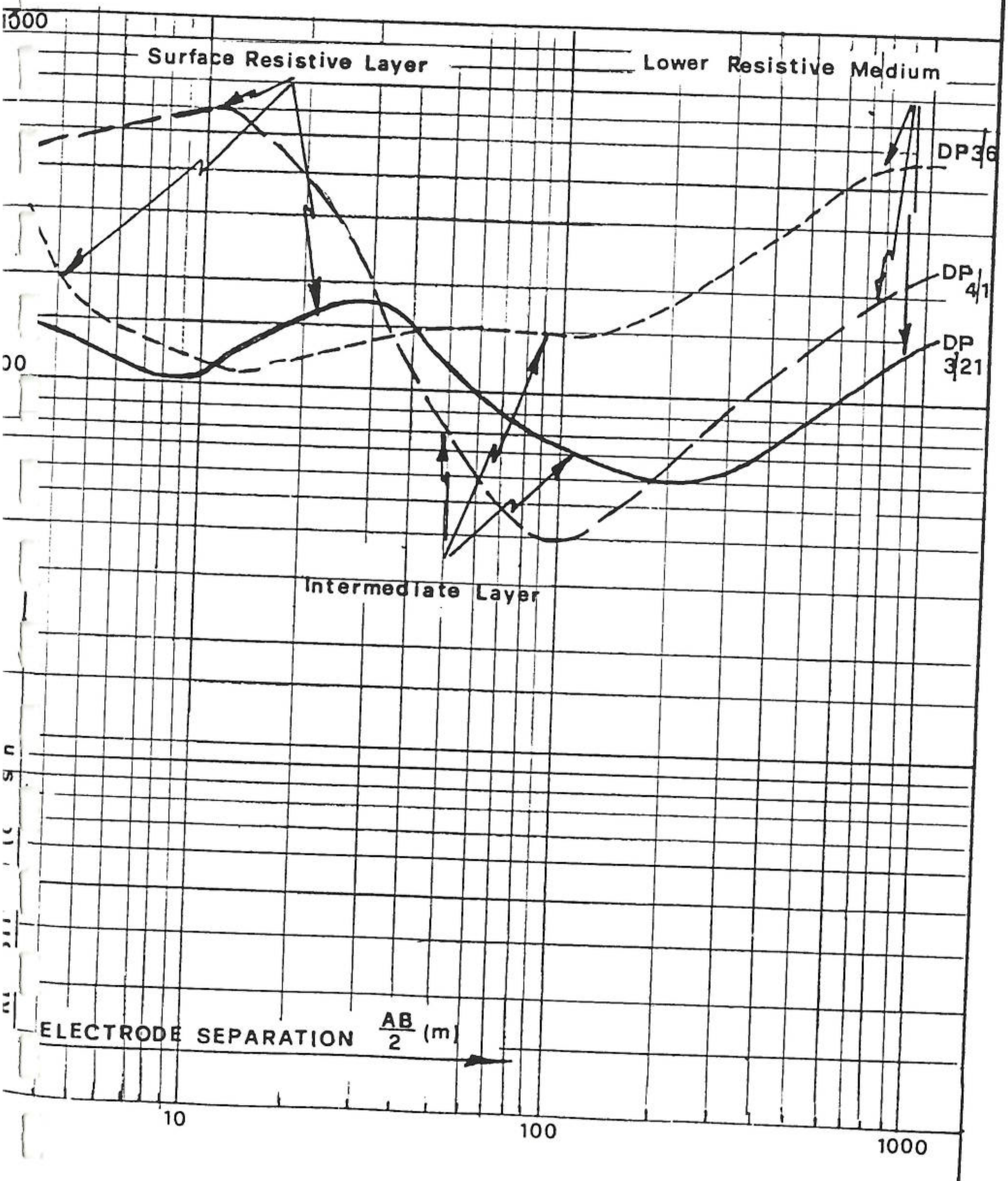


FIG 7.2

Resistivity (A B=400 m)

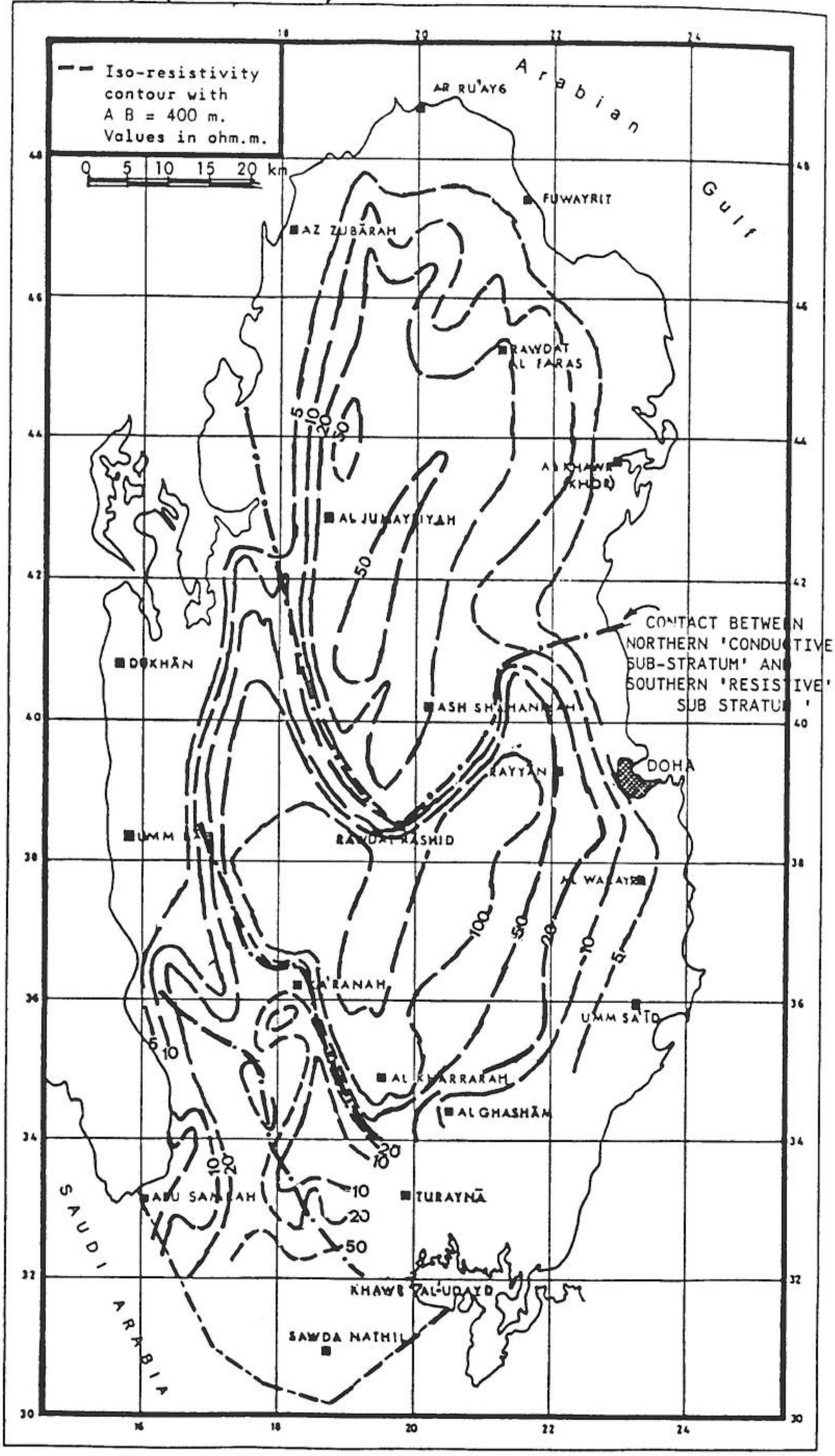


FIG: 7.3

Resistivity (A B =600 m)

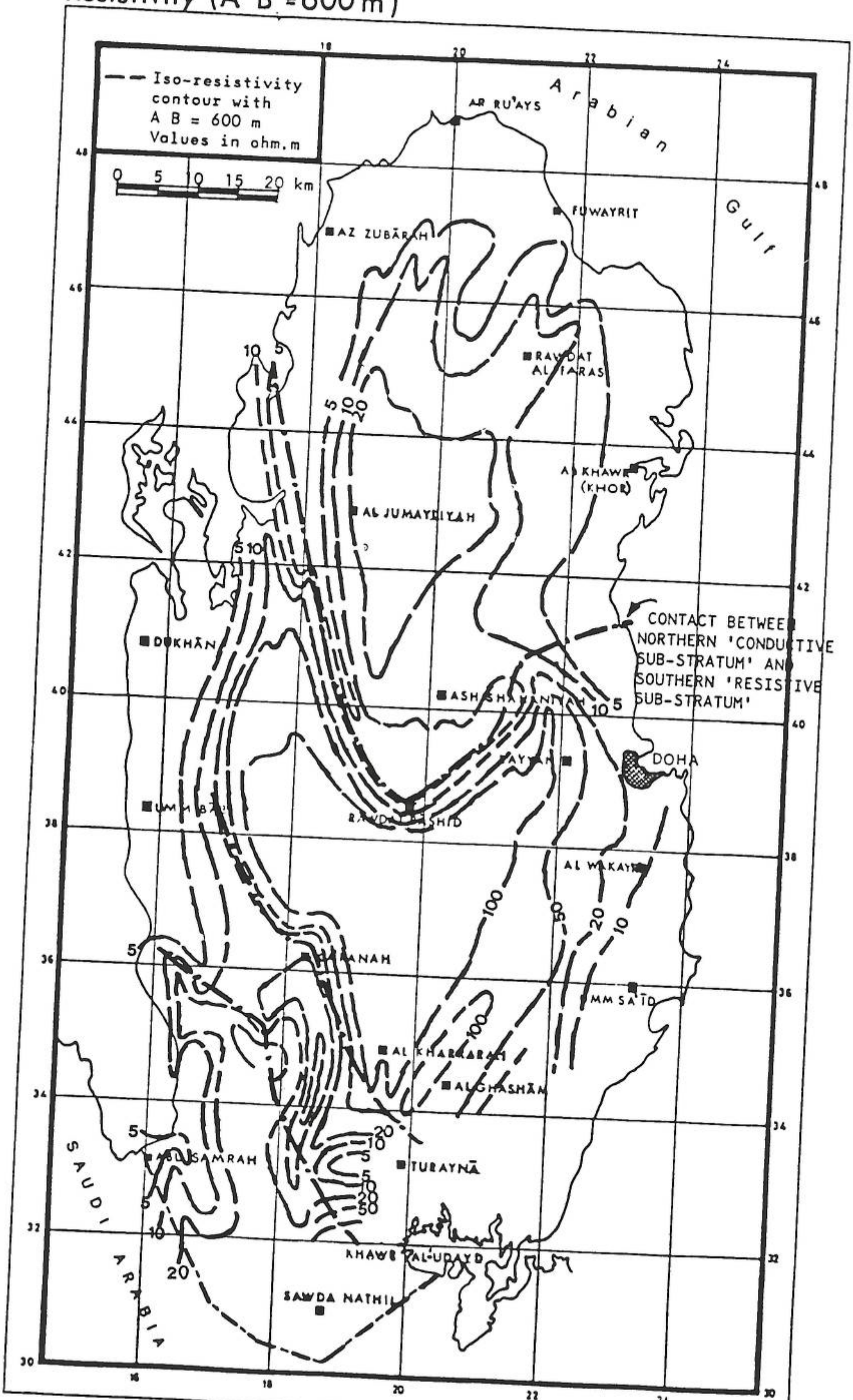


FIG 7·5

One major result of this survey was to highlight the need for a more extensive data base to (a) define precisely the freshwater - salt water interface geometry in northern Qatar and (b) permit the presentation of a clear model of the conditions in southern Qatar.

7.2.3 Geotest (1975)

Geotest (1975) were awarded the contract by FAO to carry out the additional survey as an integral part of the Project with the following specific purposes :-

- define more accurately the northern freshwater body,
- determine the conditions which defined the boundary of the northern zone and created the separation of two quite distinct hydrogeological province,
- provide a clearer model of the conditions in the southern provinces and particularly deliminate those areas where conditions similar to those of the north were present, as targets for exploratory drilling for possible freshwater reserves.
- evaluate the extent of the Abarug (Alat) Dolomite Limestone in the southwest so as to permit a proper appraisal of the shallow artesian aquifer in the Abu Samra area, close to the border with Saudi Arabia.

The survey commenced in October 1975 and a total of 260 LP arrays were made along 19 profiles. All except two were aligned east-west and were designed to extend and infill between the CMP profiles so as to increase most economically the data available for an over-all interpretation including a reappraisal of previous records. Almost all the LP were made using a Schlumberger array with AB length of 1400 and 1000 m, though one at 2000 m near bore-hole AM2A at Saudi Nathil and four at shorter than average separations were also carried out.

The increased data base and reappraisal of all previous work confirmed on geophysical evidence the basic subdivision first outlined by Le Grand Adsco (1959) and confirmed and elaborated by CMP (1972).

- above, a <u>surface layer</u> with resistivities varying widely from 10 to 15,000 ohm.m., corresponding to dry rocks of several lithologies, above sea level, which itself may be subdivided. The highest resistivity was recorded from dry sandy material.
- below an <u>intermediate layer</u> with resistivity ranging from 0.2 to 130 ohm.m. indicative of water bearing layers or aquifers of varying lithology containing water of variable salinity.
- a <u>substratum</u> marked by the great difference in its resistivity between north and south Qatar. In the <u>north</u> it is highly <u>conductive</u>, with resistivities of less than 3 ohm.m. and is recognised as the Umm er Radhuma Formation containing saline water beneath the freshwater body. Similar conditions apparently occur also in a belt along the Dukhan anticline and beneath some depressions in the southern area. Beneath the remainder of Qatar, the <u>south</u> and <u>west</u>, a <u>resistive</u> substratum was recorded with values in excess of 300 ohm.m. which Geotest interpreted as denser 'dry' rock with a lower fracture pattern and porosity.

The <u>intermediate layer</u> assumes major importance as the reservoir of useable groundwater reserves and the following analyses is pertinant.

It is generally assumed, from experimental evidence, that the conductance of a clean formation (with no appreciable clay content) is proportional to the conductance of the water it contains as only the water conducts an electrical current. The reciprocal, resistivity, therefore is also proportional and the proportionality, a constant termed the 'Formation Resistivity Factor', F., is derived from

$$F = \frac{R_f}{R_w}$$

where R_f = Formation or aquifer resistivity

R_w = Water resistivity

For a given porosity the ratio of R_f/R_w remains constant for all values of R_w below about 1 ohm.m., equivalent to a conductance of 10,000 μmhos/cm. In waters of lower salinity the value of F declines as R_w rises due to the greater influence on the ratio of the aquifer rather than the water resistivity. The porosity of a formation is the percentage of the total volume formed by the voids and pores and the Formation Factor F, is also therefore a function of the porosity. While the water resistivity and rock porosity may be measured the aquifer resistivity must be determined.

Archie proposed the formula

$$R_f = \frac{a.R_w}{\emptyset m}$$

where a = rock constant, generally 1

Ø = total percentage porosity

m = a rock cementation constant, generally 2 for calcareous limestone and 2.2 for dolomitic limestones.

Thus, as

$$F = \frac{R_f}{R_w}$$

so

$$F = \frac{a}{\emptyset^m}$$

Total porosity analysis from cores and by borehole Sonic, Density and Neutron Logging have given a widespread range of value from 10 to 40% for the Umm er Radhuma Formation in Saudi Arabia (GDC 1980). An average value of 30% was accepted and in support Astier (1974) calculated the total porosity of the Umm er Radhuma dolomitic limestone underlying the fresh-water body and saturated with saline water to be 35%. This value may also be applied to the Umm er Radhuma where it contains freshwater reserves. Because of its chalkier nature and the presence of variable amounts of clay, the value for the non-gypsiferous Rus Formation is thought to be much lower at 10-15%. This assumption is also supported by the evidence of generally lower borehole specific capacities. While no measurements of the gypsum-bearing Rus Formation were available, all evidence points to very low values of less than 5%.

Surface depressions are evidence of collapse due to one or more of the several factors of :

- solution of gypsum from the Rus Formation in the Depositional and Residual Sulphate Facies areas of Qatar
- the removal of the softer chalky limestones in the Depositional Carbonate Facies
- the overall and general replacement of calcium carbonate by the double calcium magnesium carbonate (resulting in a volume reduction) during the process of dolomitisation.

Where such depressions are present in any of the several facies areas of the Rus Formation, locally higher porosity values are observed, reaching even the overall conditions of the Umm er Radhuma below and giving rise to higher well yields and the groundwater storage of the many long established well fields.

Assuming a minimum water resistivity R_w = 2.5 ohm.m. (corresponding to an electrical conductivity of 4000 µmhos/cm, itself closen as an arbitrary boundary between 'fresh', usable reserves and saline water) and a total porosity of 35%, then

$$F = \frac{1}{0.35^2} = 8$$

Thus when R_w = 2.5 and F = 8, then the Formation Resistivity R_f = 20.

This may be considered as the lowest formation resistivity to delineate the boundary of 'fresh' useable reserves, having taken into consideration, water resistivity, total aquifer porosity and utilising generally accepted rock constants. Values between 10 and 20 ohm/m indicate brackish water while less than 10 indicate saline water. Values of less than 3 ohm/m were encountered in the highly saline coastal sabkha deposits.

Using this value, a contour map of the base of the freshwater body was prepared and this is presented as Enclosure 3. The concept of the Substratum is also of considerable importance and is further elaborated. To the limits of penetration of the equipment and methods used the Formation Resistivity of the rocks below the freshwater body were evaluated and revealed the basic subdivision as follows :

- In northern Qatar the freshwater reserves rest on a conductive body with resistivities generally lower than 3 ohm/m.
- In southern Qatar the rocks below the Intermediate Layer (the supposed water bearing zone) have resistivities in excess of 300 ohm/m and are deemed to be "less fractured, compact and dry".

A line marking the boundary between the Conductive and Resistive Substratum provinces is marked on Enclosure 3 and on Figs. 3.30, 7.3 and 7.4. An area of conductive rocks within the basically resistive southern province was also determined and this appears as a southerly prolungation of the Dukhan anticline. To the north of this boundary the contour lines indicate the regular shape of the freshwater body which follow the shape of the coast line with irregularities caused by saline water intrusion due to over-extraction. To the south of the line the highly irregular contour pattern reveals the problems of interpretation in this area and the considerable influence of the larger and deeper depressions which characterise the southern area.

It was also an intention that the survey should investigate the nature of the shallow artesian aquifer, of comparatively freshwater (2500 ppm) that exists close to the border with Saudi Arabia at Abu Samra. However, the extent of this aquifer could not be determined due to the very low resistivities (less than 1 ohm.m.) of a highly conductive surface layer which varies in thickness from 5 to 25 m, and corresponds to the recent deposits of sabkha and aeolian sand containing highly saline groundwater and evaporites.

While the low resistivity of the brackish water within the Alat aquifer is recognised, the horizon is interpreted as being in connection with the supposedly water bearing Rus Formation further to the east. However drilling and testing in the southern area has not substantiated the above hypothesis and a re-interpretation has been carried out. Deep drilling at P33 within the area of very thick (130 m) gypsiferous Rus Formation west of the Dukhan anticline has revealed water of high salinity (EC 35,000) at the top of the Umm er Radhuma Formation at -184 m. No groundwater was encountered in the Rus. In the southwest, therefore, a thick, highly resistive and dry Rus Formation is underlain by highly conductive Umm er Radhuma Formation. At P34, within the supposed zone of conductive Umm er Radhuma beneath aquiferous Rus Formation along the southward extension of the Dukhan structure, the Rus was found to be devoid of gypsum and consists rather of soft marly chalk, not the expected and typical dolomitic limestone, and was also devoid of groundwater. The top of the Umm er Radhuma is also dry and it was not until drilling reached some 17 m below the top of that Formation at -30 m that the usually prolific aquifer was encountered containing water of 15,000 EC.

Project drilling which reaches the Umm er Radhuma Formation in the south has indicated that while this Resistive Substratum supposition may hold for the central-south and the southeast, the rocks of the Intermediate Layer in the extreme south and the southwest are not aquiferous and the Resistive Substratum contains water of high salinity and very high values of porosity and transmissivity. It is suggested that the Sulphate Facies Rus Formation, formed of considerable thicknesses of gypsum with high resistivity values and little groundwater except in well developed depressions, has masked the true nature of the underlying Umm er Radhuma Formation in the southwest and extreme south. The elimination of the southwest margin of the Dukhan structure "corridor" would permit a more viable interpretation of the situation. Drilling within the corridor area, at P31, P15, P34 and P13 has indicated the true nature of the Umm er Radhuma aquifer in the areas over the Dukhan structure where gypsum is absent and masking is not therefore a problem.

Further exploratory drilling and logging to considerable depth in the centre south and southeast is required to comprehend more completely the situation and identify the effects of the variations of lithology and thickness of the Rus upon the underlying Umm er Radhuma Formation groundwater situation.

7.2.4 IDTC/Geoterrex (1979)

In 1978, as part of the "Investigation of the Development Potential of Mineral Occurrences in Qatar", undertaken by Seltrust Engineering Limited for IDTC, Geoterrex Limited flew an airborne electromagnetic survey to delineate the more conductive materials close to the ground surface. By recording the decay of transient electromagnetic fields, generated in the near surface layer by high frequency pulses, a continuous measurement of apparent surface resistivity is possible. The technique penetrates to about 150 m in resistive environments.

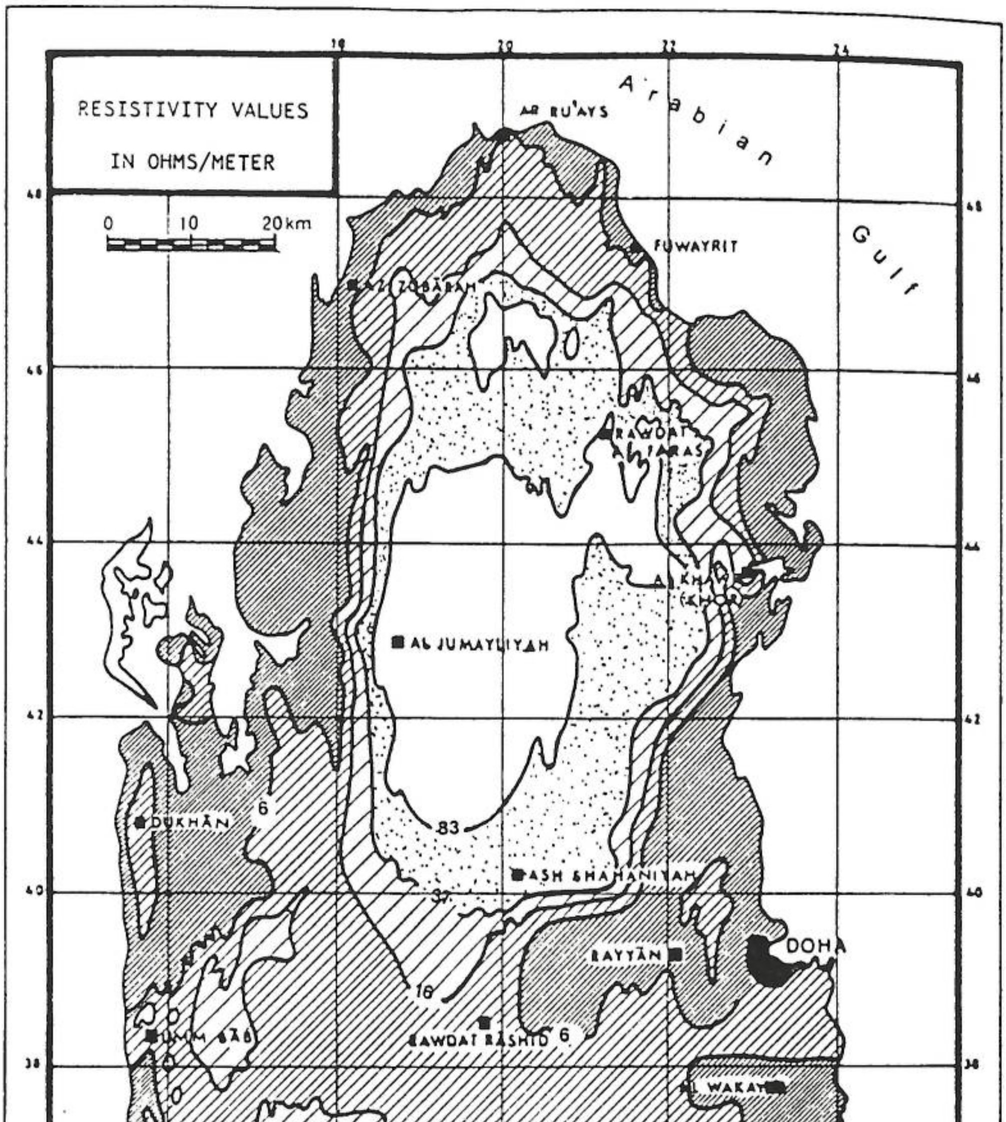
The purpose of the survey, carried out in addition to the primary objective of the assessment of mineral potential, was

- to define areas of higher resistivity where the near surface layer does not contain saline water or other conductive material,
- to provide airborne resistivity data that can be compared with existing geological, geophysical and hydrogeological data.

A total of 59 East-west traverses were flown with a separation of about 3 km., and each profile utilised sea water conditions at either end for calibration purposes. The results of the survey are presented as an isoresistivity map : Fig. 7.5 and a comparison between the airborne survey map, Enclosure 3, Enclosure 4, and Enclosure 5 suggests definite correlations.

A zone of highly conductive material (< 6 ohm.m.) surrounds Qatar, generally between 5 and 15 km wide, forming the coastal belt. This belt is narrow in parts of the north and northeast whereas at the west coast, the areas of the Dukhan sabkhas, north and west of Doha and along the southeast coast and the southern border it is much wider.

In large part, this depicts the major sabkhas and low lying saline coastal flats. However in the areas of Al Wakayr, between Doha through Rayyan to Rawdat Rashid and northwards towards Al Khawr and on the northwest coast between Grid latitude 42 and 46 North, salt flats are not a feature, and the survey has detected saline groundwater lying at a shallow depth within the limestone and dolomite aquifers. The irregular shape of the northern part of the higher resistivity area, centred on Al Gaiyah along a line between Al Khawr and Az Zubarah is also indicative of a breakdown in the otherwise regular progression of the isoresistivity contours inwards from the coastline. The centre of the zone of highest resistivity also shows a shift westwards from the axis of the peninsula due to the greater development of agriculture in the east than in the west causing a decline in the



NEAR-SURFACE APPARENT RESISTIVITY
(From Airborne Survey by Geoterrex Ltd)

Fig. 7.5

freshwater reserves and their displacement by more saline groundwater.

The position and shape of the 6 ohm contour northwest of Rayyān is seen to follow the pronounced anhydrite solution scarp (Figs. 3.11 and 3.13 and discussed in Chap. 3.2.3.2) even more closely than the Northern Conductive - Southern Resistive Boundary defined by the landbased resistivity surveys. The deviation between the solution scarp line and 6 ohm.m. line in the area of Umm el Mawage and Rawdat Rashid indicates both that the airborne survey has not mapped the solution scarp only and that the longer term pumping in these areas has resulted in a widespread thinning of the freshwater body and displacement to the near surface layers by saline water from deeper within the Umm er Radhuma Formation.

South of Grid 38 North, the apparent resistivity map show a complex pattern of isolated resistive areas. While, overall this may appear as a highly variable and complex equivalent of the northern fresh groundwater body, drilling investigations so far carried have revealed

- that the pulse generated transient electromagnetic fields, being non selective, do not distinguish between freshwater and thicker than average resistive overburden and the resultant trace portrays the dominant factor only. Thus, in the south where many outliers of thick, dry Dam Formations are present, the map records their outcrop and not the presence of freshwater in the aquifers below.

- the supposed area of considerable potential along the Abu Dhabi road has revealed, on exploratory drilling so far carried out, that the Rus Formation, while in the main gypsum - free,consists of high resistivity chalky marl along the southward extension of the Dukhan anticline. The top layers of the Umm er Radhuma are also marly, and the groundwater, when penetrated, is saline.

- the area of the Abu Samra freshwater reserves, <u>in Qatar</u>, is very small, indicated as an area of some 30 km^2 in which the apparent resistivity exceeds 16 ohm.m., appropriate to the R_f value of 20.

7.3 BOREHOLE LOGGING

Much detailed logging of deep, large diametre oil and gas exploration and production borehole has been carried out by the specialist logging companies on behalf of the oil companies. Whilst the upper sections of these boreholes are generally of little interest to the companies and the drilling diametre, often in excess of 20" to provide for the installation of large sized casing to considerable depth, introduces technical difficulties of obtaining results from the formation rather than the drilling fluid, some useful logs are available. In the early years of exploration drilling shallower, small diametre boreholes were sunk to provide structural data and logs from these are very valuable.

In neighbouring areas borehole geophysics has also been used in deep drilling for groundwater with specific interest in the characteristics of all potential aquifers and aquicludes.

In ascending stratigraphic order the regional conditions may be summarised as follows :

7.3.1 Umm er Radhuma Formation

In Bahrain, the formation lithologies of limestones and dolomitic limestones give low gamma counts, 5-10, and resistivities of about 5 ohm.m. Towards the base, in marly limestone the gamma counts rise gradually to about 50 and even exceed 100 at the contact with the under-lying Aruma Formation. Resistivity varies little with this change in lithology but declines in the Aruma to 1-3 ohm.m. in the predominantly shaley facies.

In Saudi Arabia the resistivity varies with the facies, being generally about 25 ohm.m in the predominantly argillaceous limestones of the northern area, rising to more than

100 ohm.m. where gypsum is present. In the south, values average 50-60 ohm.m. in the variable calcarenite, dolorenite and dolomite facies, which are also typical lithologies of the Qatar peninsula, rising to between 100 and 200 ohm.m. where the dolomites are homogeneous and contain freshwater in the top 50 m of the Formation.

Gamma ray logs permit the identification of the Umm er Radhuma Aruma contact by a rise from the low 10 - 20 cps of the northern sulphate facies and the 25 - 30 cps of the southern carbonate facies, to between 50 and 100 cps in the shale lithologies of the Aruma. The Aruma is also generally more compact and less porous and has a lower resistivity than the overlying Umm er Radhuma.

7.3.2 Rus Formation

Logging of the Rus Formation reveals the highly variable resistivity of the typical sulphate lithology in Saudi Arabia. Values average about 100 ohm.m. for the 16" probe in the thick anhydrite beds and between 200 and 300 ohm.m. for the 64" probe, falling to about 10-20 ohm for both sensors in the shales and saline-water-bearing dolomities. In Bahrain, the typical thick anhydrite-bearing section reveal similar logging characteristics with very variable resistivity and peak values at anhydrite beds.

The gamma ray shows the main peaks, up to 100 cps at the shale horizons, with smaller peaks, 20 - 30 cps, at the anhydrites with lows, less than 10 cps, at the limestones and dolomites. In the Rus sulphate facies areas, the Rus - Umm er Radhuma Formation contact, generally difficult to define, has been placed at the level below which anhydrites are absent and log :istivities decline. Where the Rus has lost anhydrite and argillaceous material due to s. ution and removal, the residual chalky dolomitic limestones with quartz geodes, large voids and solution networks, give very low resistivity values.

7.3.3 Dammam Formation

In Bahrain and Saudi Arabia, the details of logging results are as follows :

	Formation	Gamma ray (cps)	Resistivity (ohm.m.)
Upper Dammam	Alat Limestone	10 - 15	Lower (5)
	Alat (Orange) Marl	0 - 30	Very low (< 1)
	Khobar Dolomite	Very low (< 5)	High (15+)
	Khobar Marl	50 + declining upwards to 5	Generally high (15)
Lower Dammam	Alveolina Limestone	50	High (20)
	Sharks Tooth Shale Group	Very high 100+	Low (< 10)

In Bahrain, high resistivity in the top 5 m dolomite of the Khobar Dolomite Member is associated with the first loss of circulation during drilling and reduced rates of penetration. In the Sharks Tooth Shale Group a marked increase in gamma activity occurs in zones of grey and bluish shales.

In Saudi Arabia, where the Saila Midra Member is developed as shales (in marly Rus Formation facies areas),the gamma counts are high (100+ cps). This feature is frequently used to distinguish the Dammam/Rus Formation contact in logged boreholes where cuttings recovery is poor and the Saila Midra is of a shaley facies. Elsewhere, in sulphate facies Rus Formation areas (where the Lower Dammam is usually marly rather than shaley) the gamma is reduced to about 25 cps, with lows of 5 and peaks of 60 cps. The Khobar and Alat Marls are not well distinguished, though peaks of 30 - 40 cps do occur at the most marly horizons. Resistivity is generally low, less than 10 ohm.m., at all marly levels rising to 15 ohm.m. at the denser limestone and dolomitic limestones. A marked and abrupt rise to 100 ohm.m. plus occurs at the anhydrite-bearing Rus contact with the marly Midra Saila Member above. Where the Rus is marly and calcareous and the Midra shaley, the rise is more gradual from 30 ohm.m. in the Midra to 50 ohm.m. in the Rus Formation.

7.3.4 Logging in Qatar

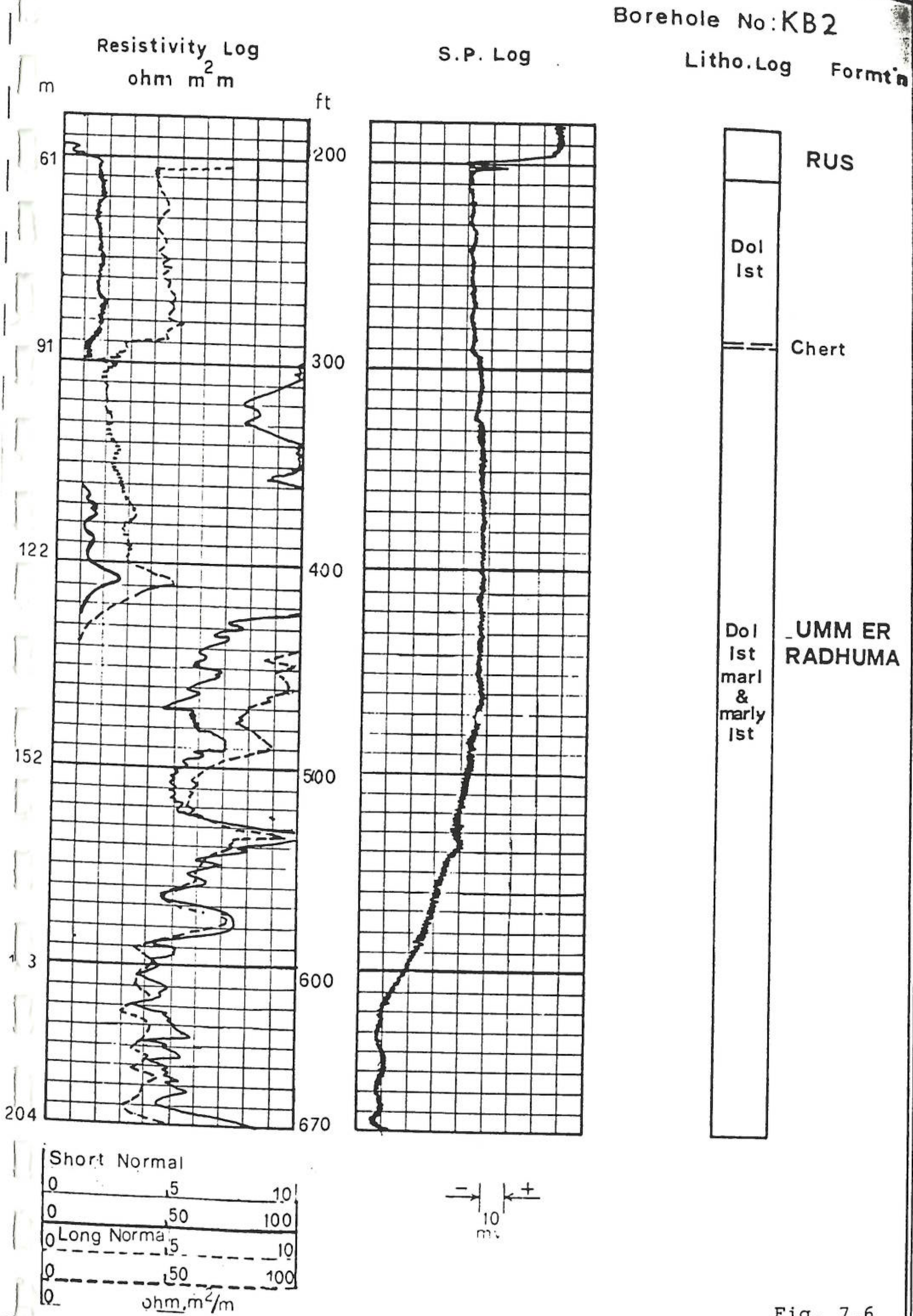
In Qatar, the post Aruma formations have received little logging attention but data from early boreholes are valuable.

Logs for boreholes KB2 and SH9 drilled in 1953 in north Central Qatar are presented as Figs. 7.6, 7.7 and 7.8. SH9, the more northerly, is located within the Depositional Carbonate Facies and KB2 at the boundary between the Depositional Carbonate Facies and the Residual Sulphate Facies. For KB2, Spontaneous Potential (SP) and 16"/64" Resistivity (Fig. 7.6) and 18'8" Resistivity probes (Fig. 7.7) were run. The drilled diameter was 20 inches from surface to 183 m and 15 inches below and the relatively limited formation penetration of the 16" probe is indicated by the lower resistivity values when compared to the results of logging with 64" and the 18'8" probe. Only between the depths of 61 and 91, 110 to 128 and 218 to 235 m does the 16" sensor indicate resistivities above 10 ohm.m. with very occasional peaks above 20 ohm.m. The values from the three probes begin to converge below 137 m depth and below 152 m have given very similar results, with greater highs and lows from the longer probe indicating greater formation penetration.

The fluid level and casing in the borehole did not permit the logging of the Dammam and Rus Formation lithologies. However, the change from the chalky marly limestones of the base of the Rus to the permeable dolomitic limestone of the top of the Umm er Radhuma is recorded by an increase in formation resistivity from less than 20 ohm.m. to about 50 ohm.m. The thin chert horizon at about 88 m below ground level is marked by an increase in resistivity to more than 100 ohm.m for a small vertical interval on the 18'8" (Fig. 7.7) log. This horizon was not registered by the shorter probes for the reasons already given. This chert was also clearly recorded on a further log using a 32" limestone probe. Below the chert horizon, resistivity values fall abruptly to about 20 - 30 ohm.m. over the interval between 81 and 134 m follow by a further decline to less than 10 ohm.m. below 137 m depth with minimal values of only 1-2 ohm.m over the remainder of the logged profile. The first decline in resistivity is believed to indicate the markedly high permeability of the upper section of the Umm er Radhuma and the second, the contact between fresh and brackish groundwater with an interface zone of mixing between 128 m and 158 m depth. The base of the freshwater body is thus interpreted as lying at -88 m at the site of KB2.

The Spontaneous Potential log of KB2 indicates stable non-reactive conditions throughout though this is believed to be the result of the large borehole diameter and in consequence, the considerable separation between the sensor and the reaction zone at the interface between drilling fluid and bore wall. However, a noticeable decline to less positive conditions is apparent starting below -100 m and continuing to -150 m. Below this depth it is assumed that groundwater circulation has been inactive.

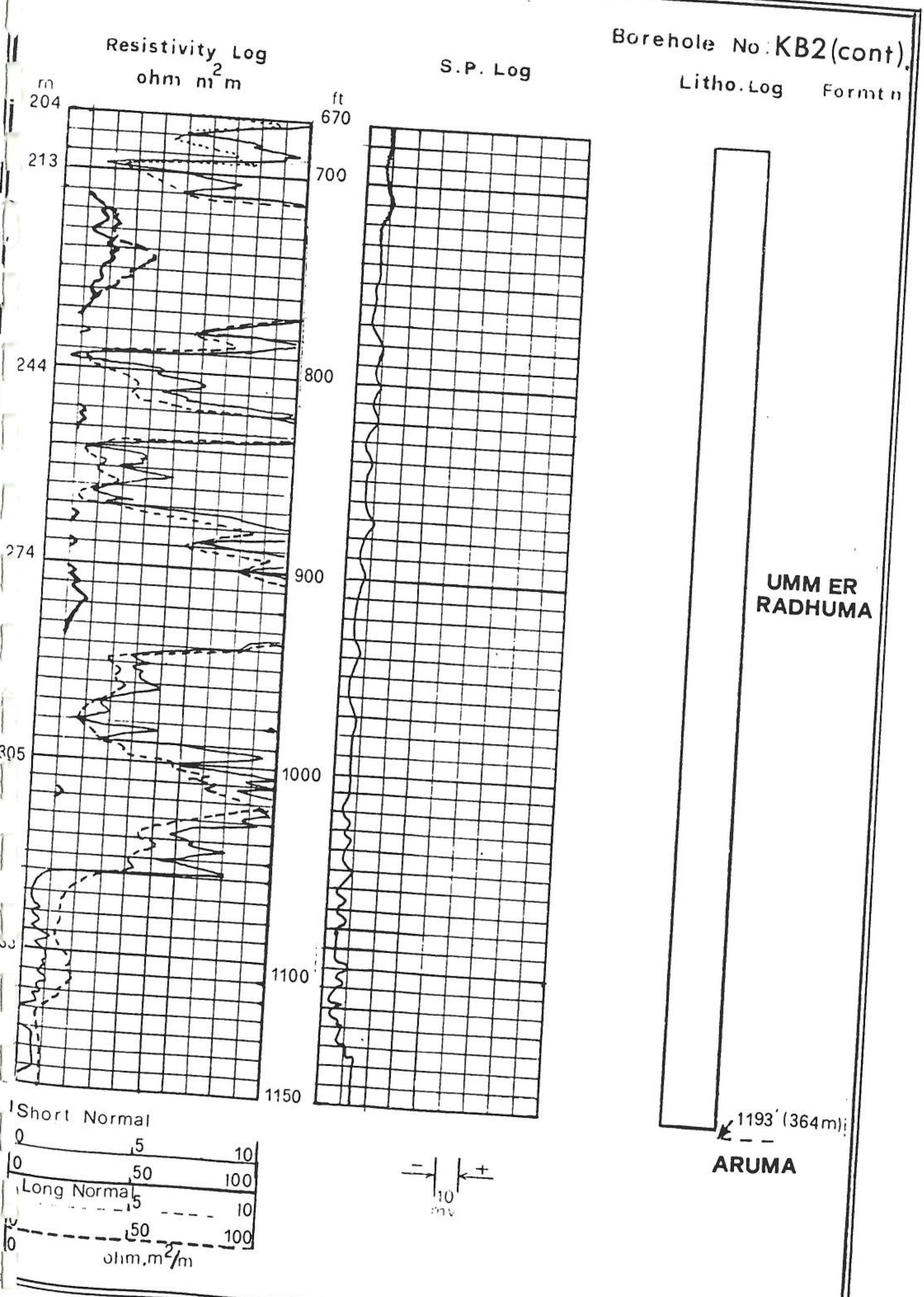
At borehole SH9, Self Potential and 16"/64" Resistivity (Fig. 7.8) were logged in a much smaller drilled diameter of 5 3/4" and 4 3/4" and without casing. The logging results are therefore much more indicative of the true rock parameters in the absence of a large radius of masking drilling fluid. Again the Dammam Formation does not feature in the logging and the lower part of the Rus has low resistivity, less than 10 ohm.m., rising to 30 ohm.m. at the contact with the Umm er Radhuma below. This rise may be caused by the presence of marly limestone and the top 14 m of the Umm er Radhuma are probably of a similar lithology. Below this moderately resistive band, the resistivity declines to low values, 10 ohm.m., for about 13 m of the Umm er Radhuma thickness. At about 100 m below sea level values fall, over a interval of 15 m., to less than 1 ohm.m. and remain so to the considerable depth of 230 m below sea level. This highly conductive unit is believed to be highly porous Umm er Radhuma olarenites and dolomites containing saline water. Thus the base of the freshwater body is presumed to be at about 100 m below sea level with a relatively thin mixing zone of 15 m between it and the saline groundwater below. Variations in resistivity of the lower part of he Umm er Radhuma point to changes in lithology with increasing proportions of marl and clay. he chert horizon, some 15 to 20 m below the top of the Umm er Radhuma, is not recorded by the logging and, in the absence of a detailed litholog it is assumed that the chert is sent.



Borehole No: KB2
Resistivity Log
ohm m2m
S.P. Log
Litho. Log
Formt'n
m
ft
61
91
122
152
204
200
300
400
500
600
670
RUS
Dol
lst
Chert
Dol
lst
marl
&
marly
lst
UMM ER
RADHUMA
Short Normal
0
5
10
0
50
100
Long Normal
0
5
10
0
50
100
ohm.m2/m
10
mv

Fig. 7.6

Borehole Geophysical Profile 7/17



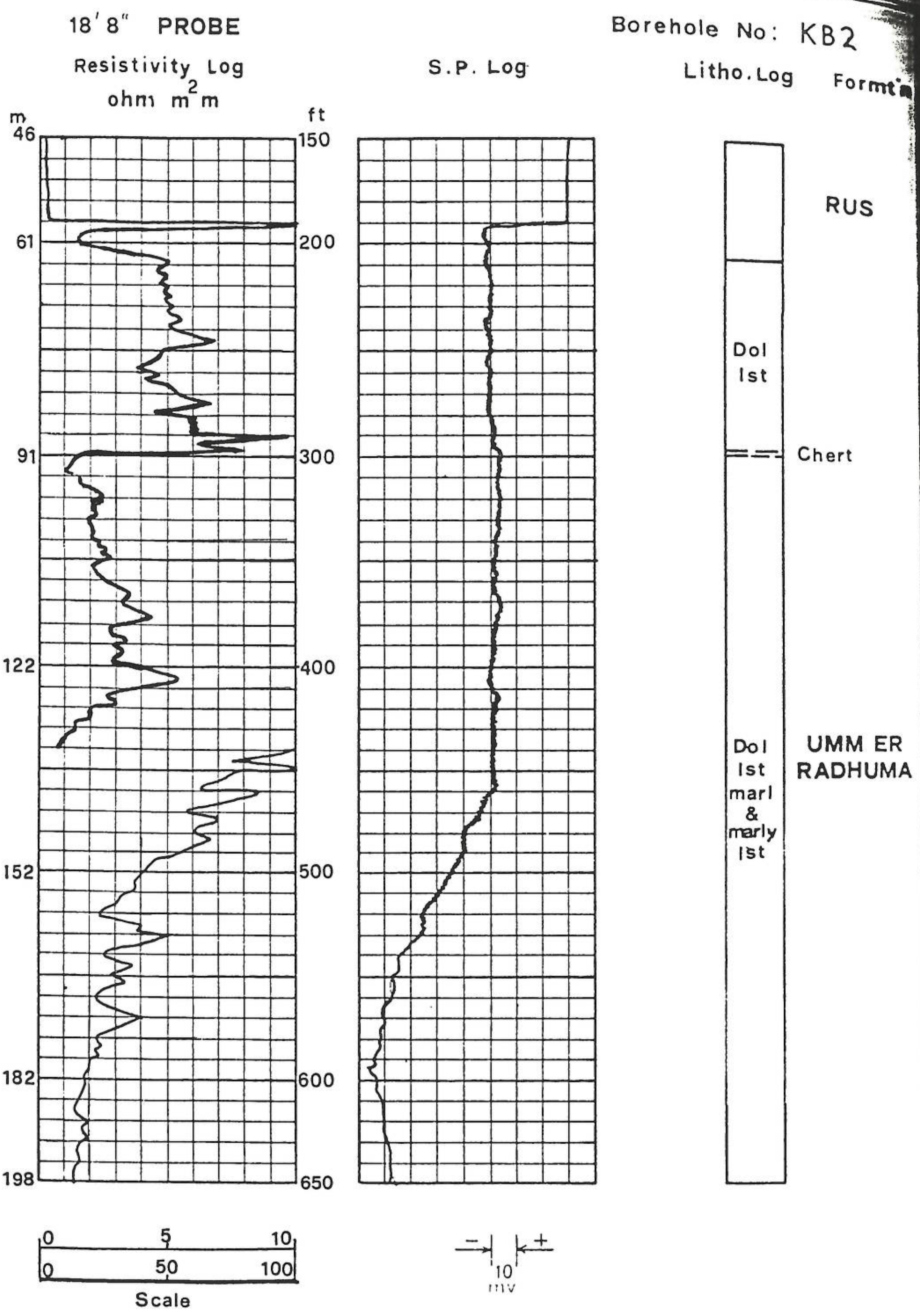

18' 8" PROBE
Borehole No: KB2
Resistivity Log
ohm m2 m
S.P. Log
Litho.Log
Formt'n
m
ft
46
150
61
200
91
300
122
400
152
500
182
600
198
650
RUS
Dol
lst
Chert
Dol
lst
marl
&
marly
lst
UMM ER
RADHUMA
0
5
10
0
50
100
Scale
−
+
10
mv

Fig. 7.7

Borehole Geophysical Profile

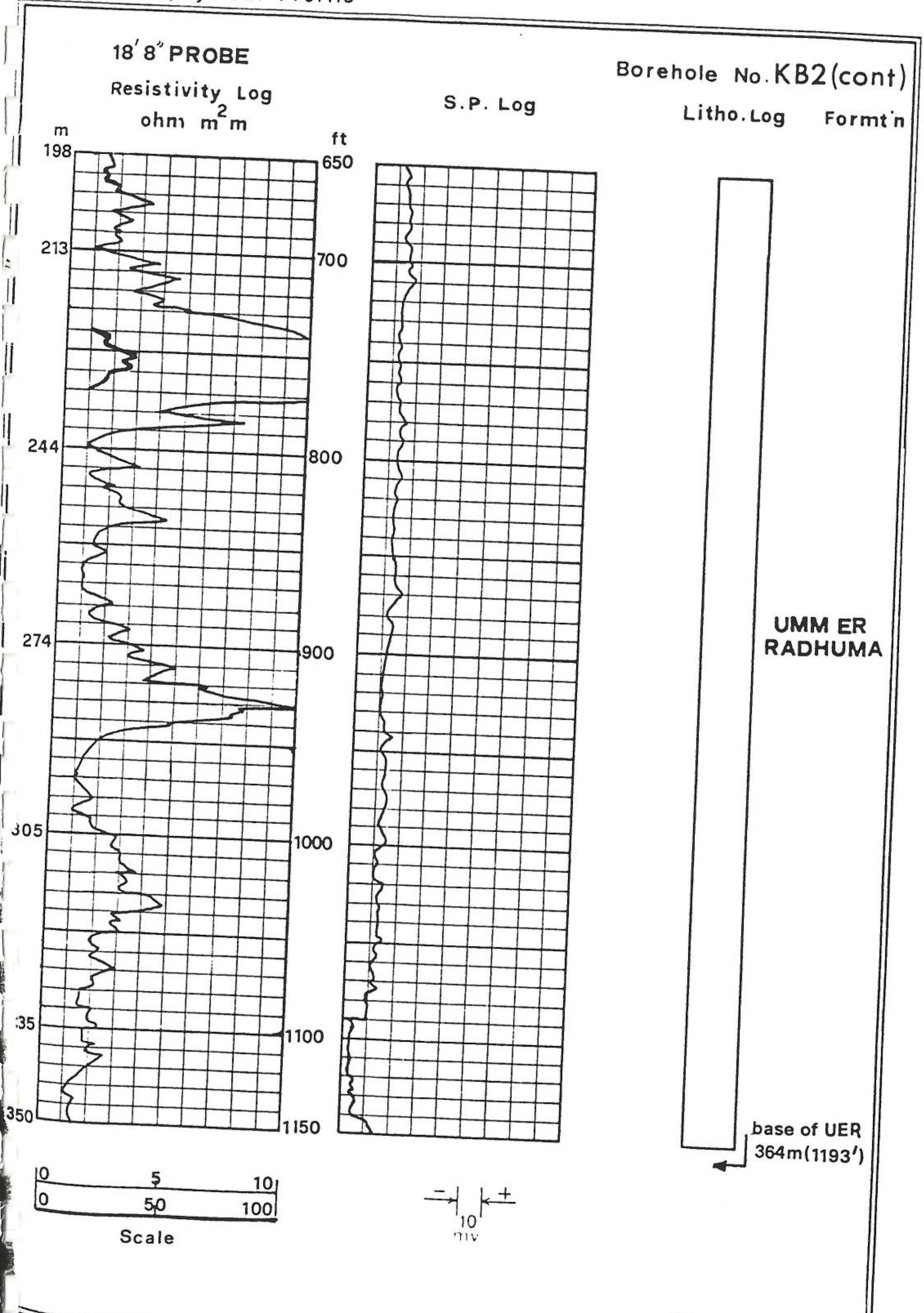


Fig 7.7 (

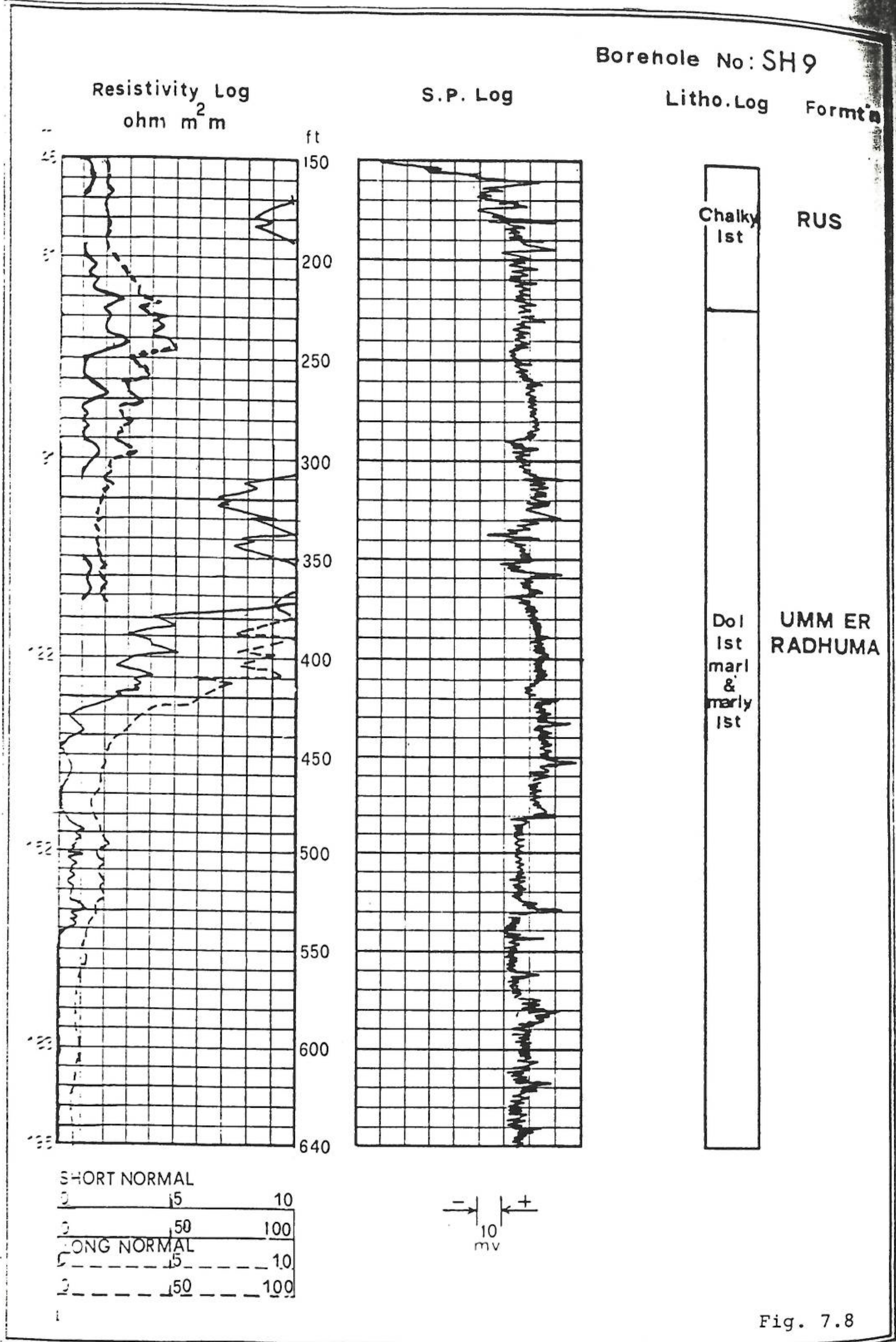

Borehole No: SH9
Resistivity Log
ohm m2 m
S.P. Log
Litho.Log
Formt'n
ft
150
200
250
300
350
400
450
500
550
600
640
Chalky lst
RUS
Dol lst marl & marly lst
UMM ER RADHUMA
SHORT NORMAL
5
10
50
100
LONG NORMAL
5
10
50
100
−
+
10 mv

Fig. 7.8

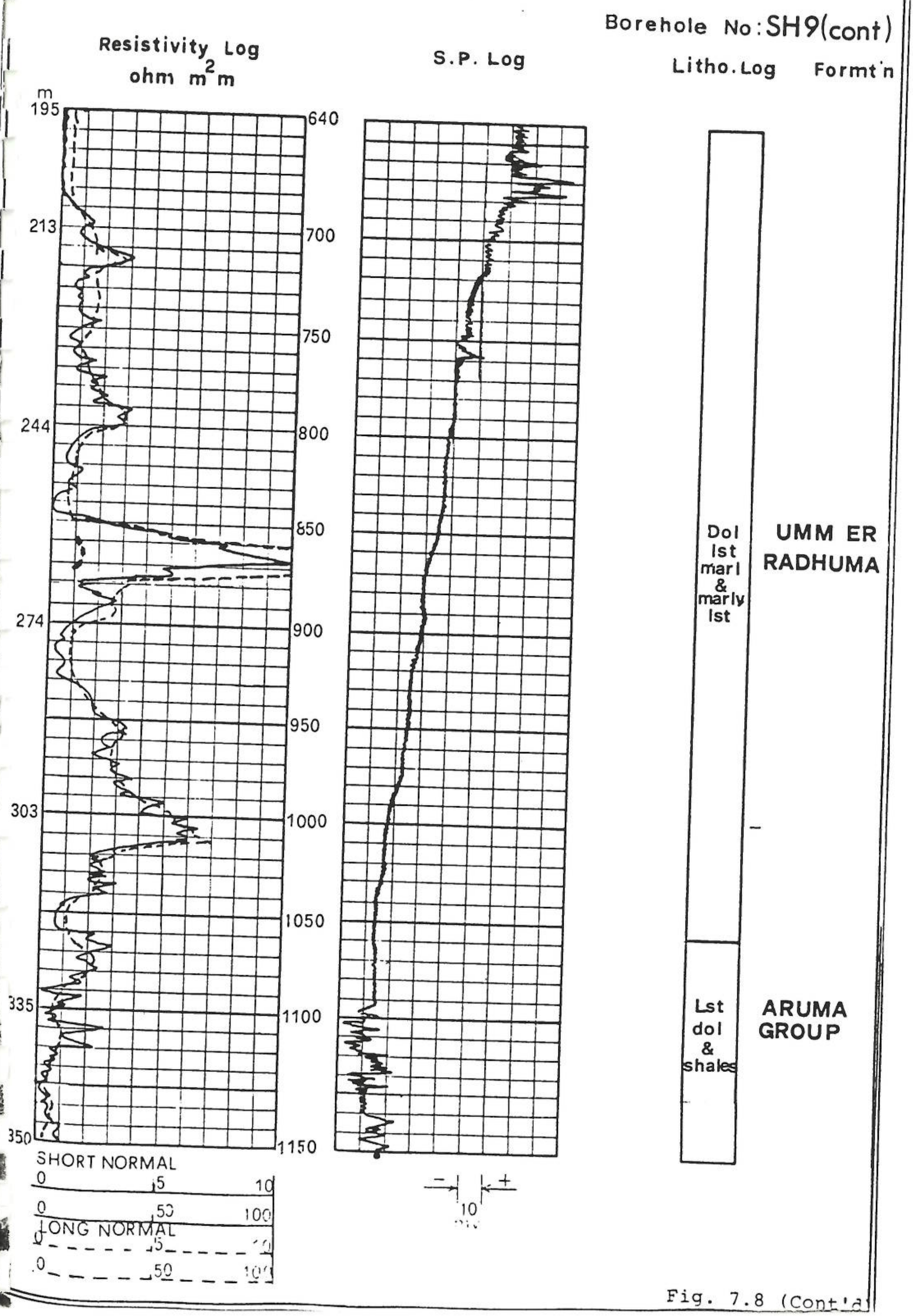

Borehole No:SH9(cont)
Resistivity Log
ohm m2m
S.P. Log
Litho.Log
Formt'n
m
195
213
244
274
303
335
350
640
700
750
800
850
900
950
1000
1050
1100
1150
Dol
lst
marl
&
marly
lst
UMM ER
RADHUMA
Lst
dol
&
shales
ARUMA
GROUP
SHORT NORMAL
0 5 10
0 50 100
LONG NORMAL
0 5 10
0 50 100
− +
10

Fig. 7.8 (Cont'd)

The SP record is consistant throughout the Rus/Umm er Radhuma with sharp positive and negative peaks indicating localised electrochemical reaction between the aquifer, the water contained by it and the drilling fluid. Only below -180 m does the trace decline to non-reactive equilibrium conditions as observed in KB2.

In 1979, a deep exploration well was drilled, again just within the Residual Sulphate Facies of the Rus Formation near the contact with the Depositional Carbonate Facies, at location KB3 and logging, using up-to-date sophisticated equipment and refined methods has yielded valuable results. The profiles from certain of the surveys are presented as Fig. 7.9 and they permit an overall close comparison with KB2 and SH9. Variations in Gamma ray values, within the 10 m of Simsima Formation available for logging are inconclusive, but the range within the upper Rus, of Residual Sulphate Facies, from a base level equivalent to about 35 cps to occasional peaks in excess of 125 cps records the lithological variety. A sonic log was also made which may be used to interpret variations in porosity, with the higher velocities occuring in the less porous units, but the results were inconclusive. The profile did however indicate numerous and large variations in velocity coefficients which are consistent with a much modified and weathered formation from which the soluble material has been removed.

Below the water table, in the lower Rus, the gamma ray activity is much reduced, consistent with a more homogeneous chalky limestone lithology and this feature continues downwards through the Umm er Radhuma with only occasional increases to moderate levels related to the presence of marlier layers within the predominantly dolomitic lithology. Some 76 m below the top of the Umm er Radhuma Formation and at a depth of -122 m the trace shows a remarkable rise to exceed 250 cps for a thin layer and this variation is also shown by a considerable increase of formation resistivity from about 2 to 20 ohm.m. for the Spherically Focused Resistivity and 50 ohm.m. for the Deep Induction Log. This unusual combination of increases is interpreted as being caused by the presence of organic (hydrocarbon) matter in the aquifer.

In general the resistivity profiles are consistent with those from the other boreholes with values 20 to 50 ohm.m. for both the Rus and the Umm er Radhuma Formations where they contain low salinity groundwater. A very rapid fall to about 2 ohm.m. occurs at a level of -74 m, some 110 m below groundlevel, and is believed to mark the change from fresh to saline groundwater conditions and thus the base of the fresh water reserves.

The chert horizon, some 9 m below the top of the Umm er Radhuma Formation, is again recorded by a sharp temporary rise in resistivity value in an otherwise regular section of the profile.

7.3.5 Project Logging

7.3.5.1 Introduction

To overcome the problem of the paucity of geophysical information on the upper formations and to provide immediately accessible information on the exploration boreholes drilled by the Project for correlation with geological and hydrogeological information generated by the description of cuttings samples and by the test pumping of aquifers, a battery-operated temperature and conductivity logging meter was purchased by the Project in 1975 and a truck mounted logger in 1978. Both instrument systems were manufactured by Robertson Research International Ltd. of Llandudno, United Kingdom.

The meter permitted the measurement of temperature - compensated water conductivity to a borehole depth of 200 m in three ranges of 0-1000, 0-10,000 and 0-100,000 μmhos.cm. Water temperature could also be measured in the range $-5^{o}C$ to $+45^{o}C$. Using this instrument some 150 borehole temperature and salinity profiles have been recorded. The truck-mounted logger, also capable of measurements in boreholes to depths of 200 m, was equipped to log water temperature between $-5^{o}C$ and $+45^{o}C$ and conductivity in three ranges from 0-1000, 0-10,000 and 0-100,000 μmhos.cm. which could be increased, by using bias adjustment of up to 100% of the range scale, to a limit of 200,000 μmhos.cm.

Borehole Geophysical Profile

KB3

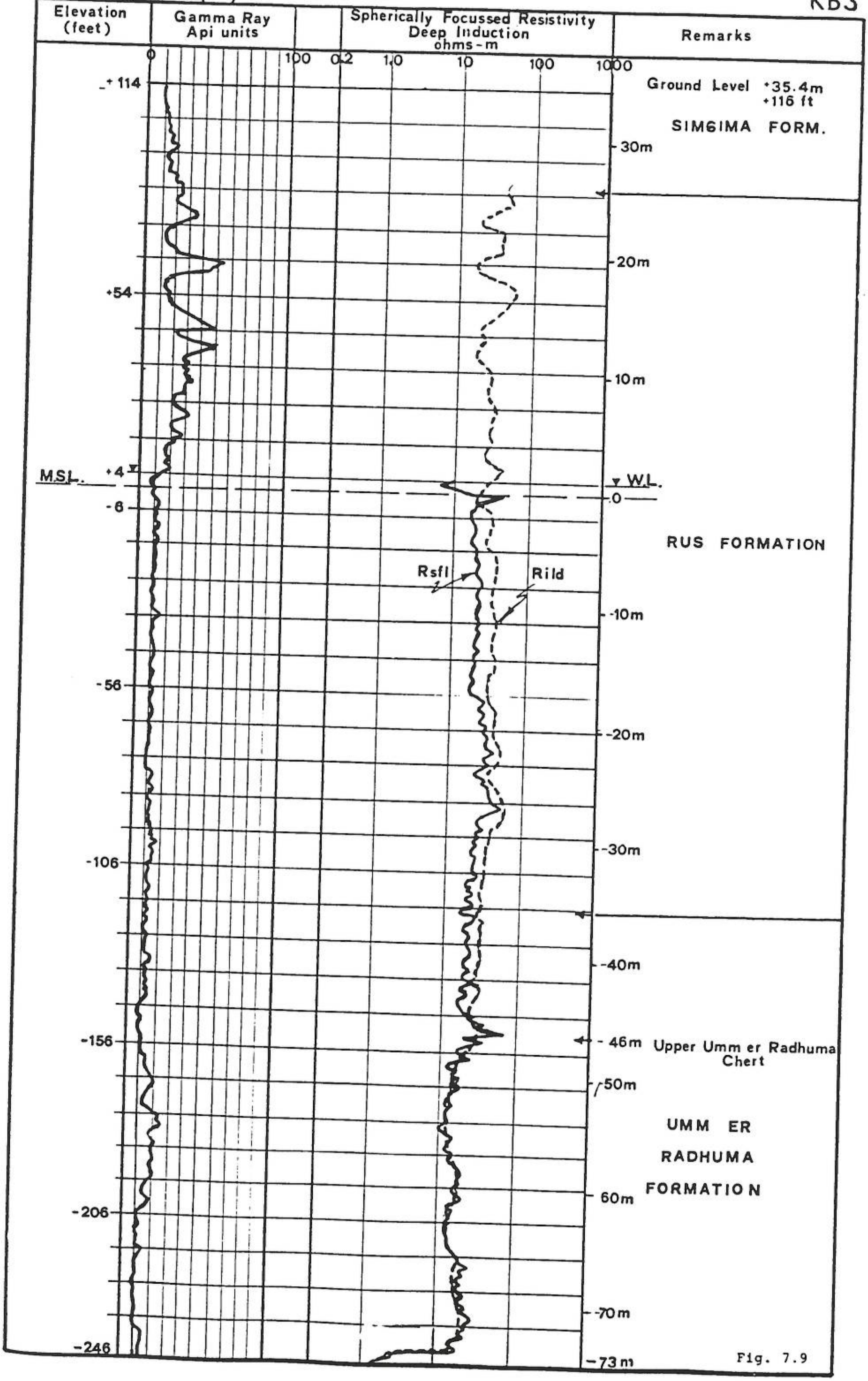


Fig. 7.9

Borehole Geophysical Profile

KB3(cont)

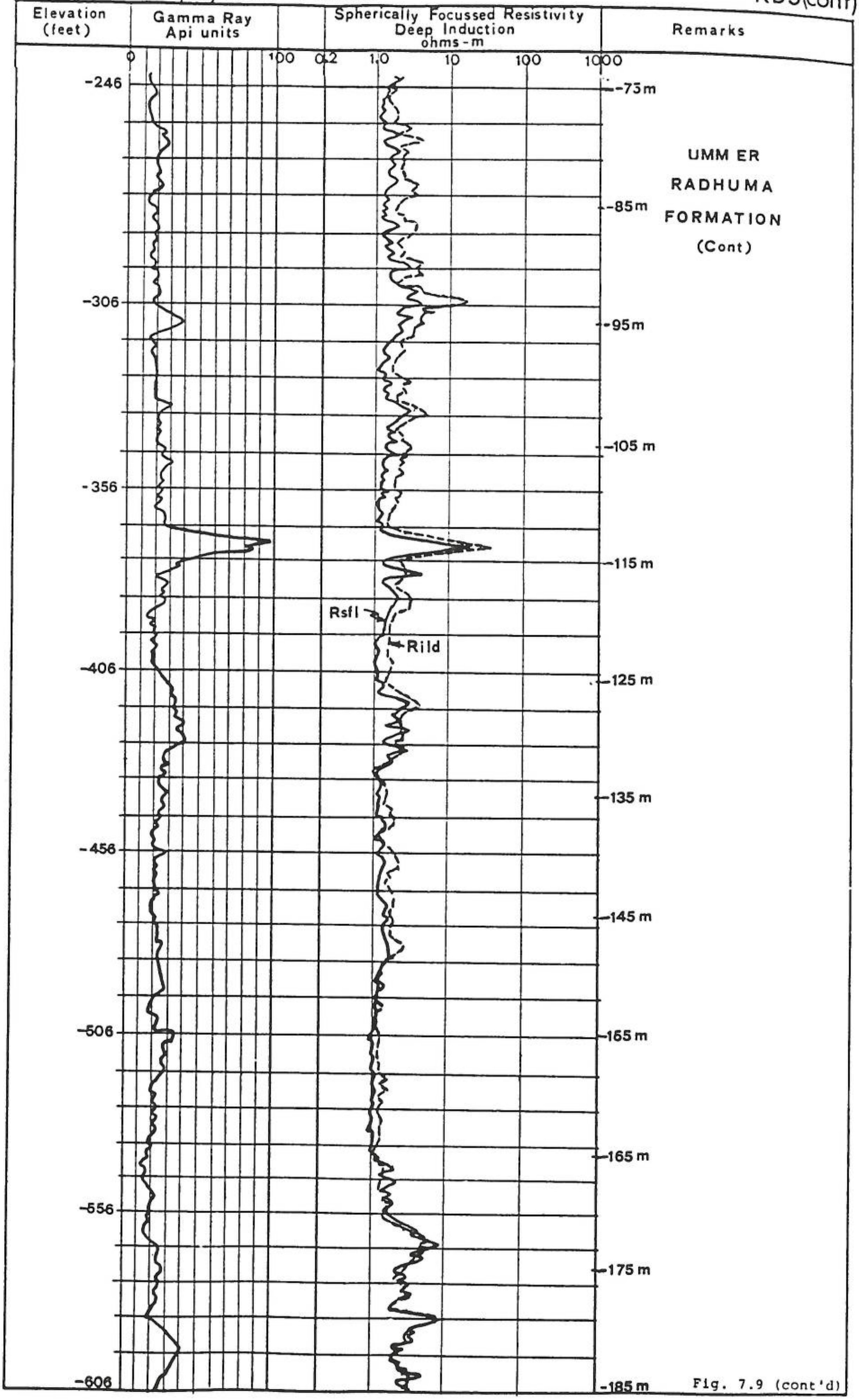


Fig. 7.9 (cont'd)

Spontaneous Potential is measurable in ranges from 0-200 to 0-10,000 mV. Resistivity, both as Single Point and Multipoint, is registered in ranges from 0-20 to 0-10,000 ohm.m. A Gamma ray system consisting of a scintillometer sonde and ratemeter module gives a output of total count of natural gamma radiation. A depth sampler was also available to obtain one litre water samples, for further laboratory analysis, from any required depth level up to 200 m below ground. A three channel recorder, attached to the control module, permitted the paper chart recording of up to three input channels simultaneously with provision for depth marking during the logging procedure. By selection, one of the channels could be switched to record the rate of change in the signal from one of the sensors thus permitting small, rapid and short duration variations to be seen clearly. Mechanical and electrical faults and break-downs have restricted the periods during which the logger could be used and insurmountable difficulties were encountered during logging in temperatures above 40°C which also reduced the periods of effective use. Nevertheless, some 45 boreholes have been logged for a total meterage of 2237 and some 60 depth-selected water samples have been taken for laboratory analysis.

7.3.5.2 Logging Results

A summary of logging surveys carried out for Project investigations are presented as Appendix 7.1. Some 53 logs have been produced for 45 boreholes for an aggregate of 2237 m of profile. Where appropriate these logs are reproduced as Project Borehole Geophysical Profiles in the Borehole Completion Reports forming Appendix 9.1. Certain logs are selected for comparative purposes and described below.

Project Borehole P27 (Fig. 7.9)

The exploration borehole drilled in the Residual Sulphate Facies area was cased to 84.9 m before the logger became available and only the gamma ray log is reproduced for the full drilled depth of 135.6 m. Other parameters are indicated for the interval between 34.9 m and the full depth. A gamma ray peak of 85 cps is notable within the upper 10 m of the Umm er Radhuma Formation and this with the smaller peak at 62-63 m are interpreted as arls at this hydrogeologically important level within the Rus - Umm er Radhuma aquifer omplex, which were not recovered during normal drilling operations. The 16"/64" profiles show very high resistivity values which are probably due to electrical contact problems reated by drilling mud penetration of the formations during the attempts to cure the fluid oss problems.

Project Borehole P22a (Fig. 7.10)

Borehole P22a also in the Residual Sulphate Facies area, of large drilled diameter, penetrates to the base of the freshwater body and the level at which this occurs, clearly corded by the conductivity profile (not illustrated), is clearly indicated also by the SP g. Below the 115 m depth the resistivity log activity also declines, although the values remain high. The peaks of the gamma log occur in the Umm er Radhuma Formation and serve to lustrate the presence of many marly and shaley bands within the otherwise vesicular omite and dolomitic limestone. The chert horizon, recorded by drill cuttings from within the Umm er Radhuma, is not shown clearly on any of the profiles.

ject Borehole P29 (Fig. 7.11)

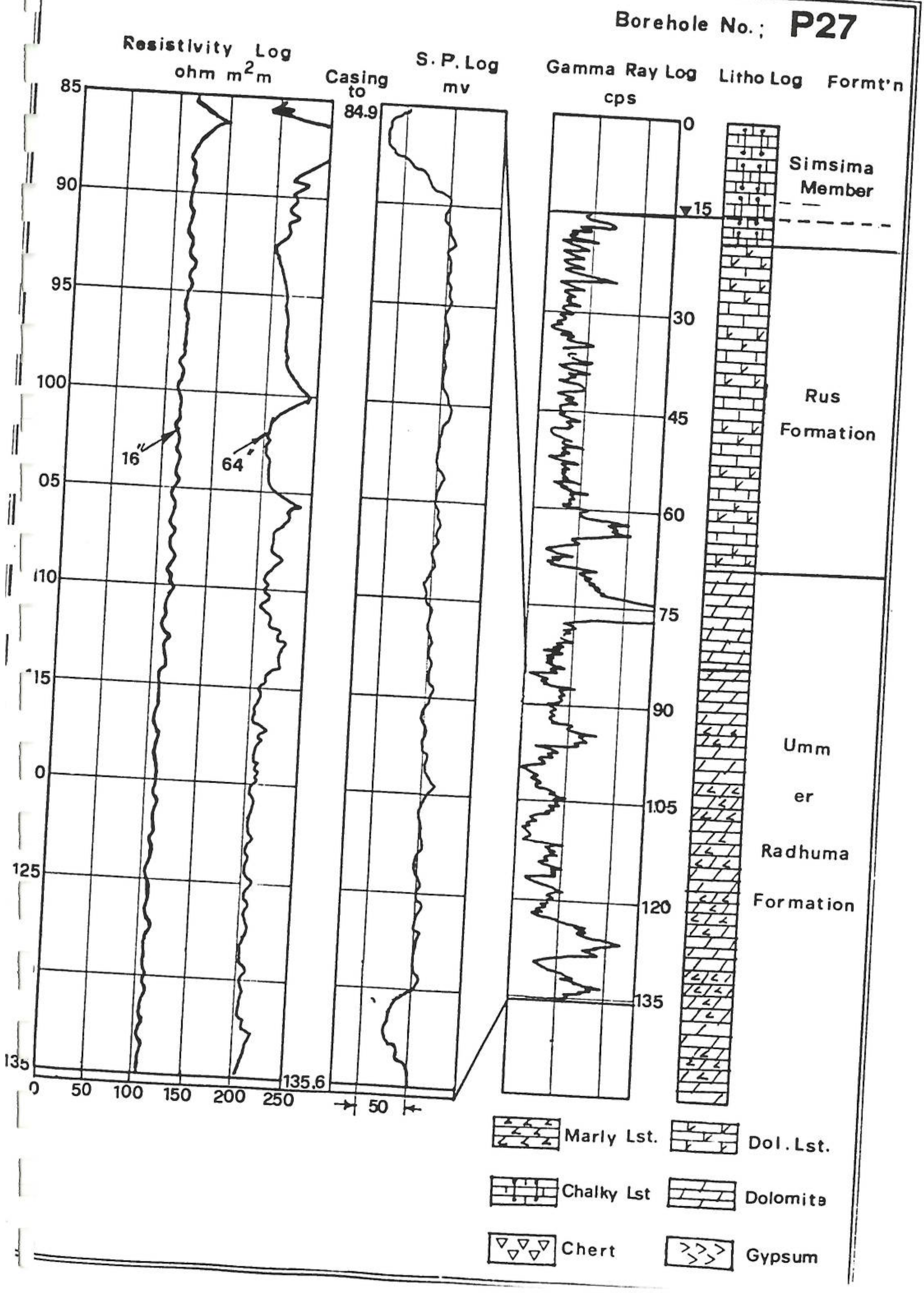
This deep exploration borehole, sited in the north western extension of the Sulphate ies area of the Rus Formation, excountered considerable gypsum in both the Rus and the underlying Umm er Radhuma Formation. This phenomenon is illustrated in the variable gamma record. The occasional peaks in the resistivity log, occurring generally at lows in the a ray profile, are interpreted as thicker compact dolomitic limestones or dolomites in the otherwise chalky and marly limestone sequence. The SP record is uneventful as, in this orehole near the northwest coast, no major changes in groundwater quality occur to mark ation in circulation conditions and there is no development of a fresh

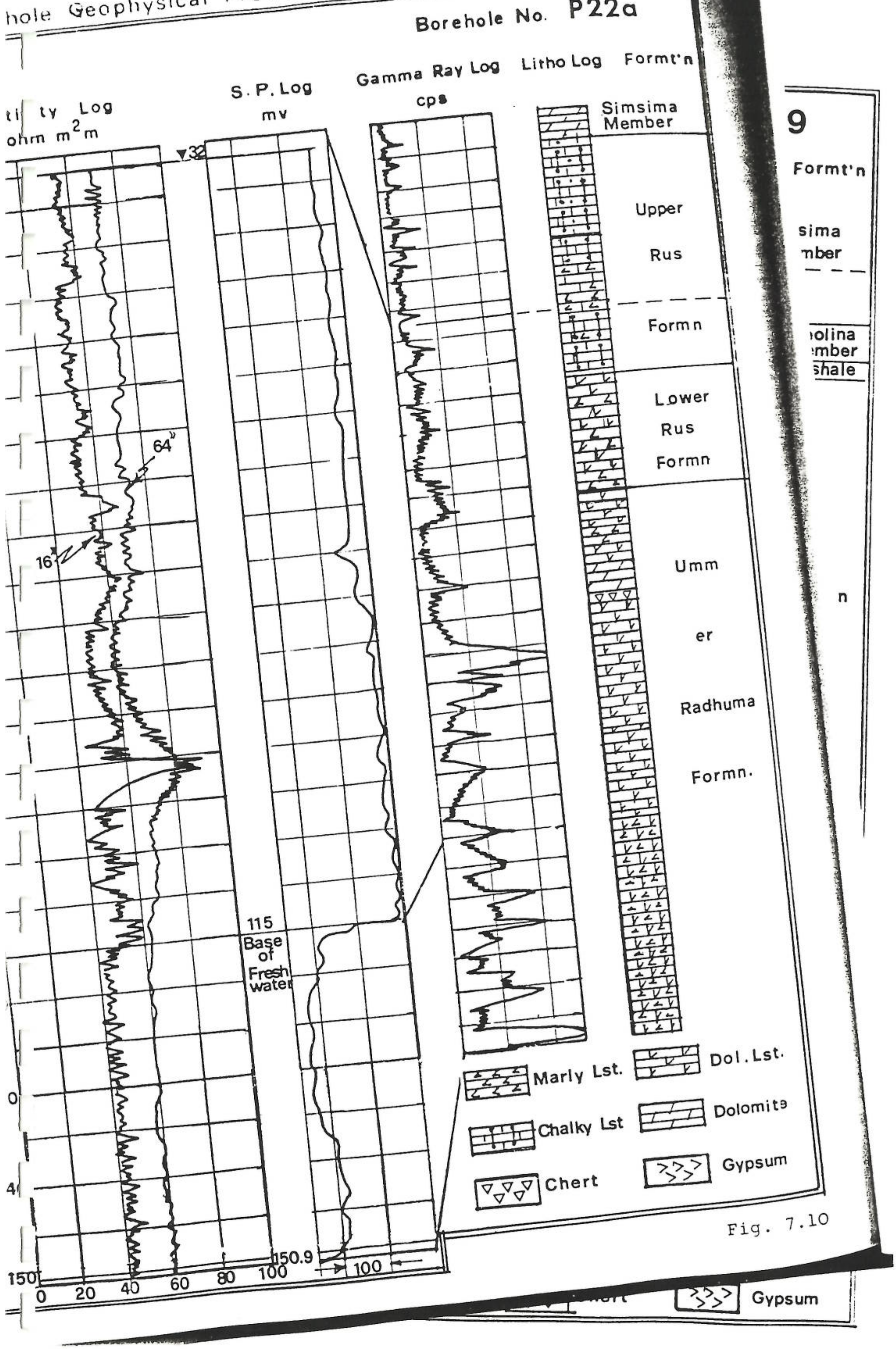
The Midra Shale Member of the Lower Dammam Formation is clearly recorded by a high in the Gamma ray record and the less argillaceous limestones throughout are marked by lows.

Project Borehole P30 (Fig. 7.12)

Drilling in Borehole P30, sited at the boundary zone between the Residual Sulphate and the Depositional Sulphate areas, could not proceed beyond 65.9 m depth due to caving problems but very slow and laboured progress at that depth indicated that the level of the Umm er Radhuma chert had probably been reached. The large diameter of the borehole and the mud fill required to prevent collapse have masked all parameters and also produced a falsely variable SP activity. The shales and clays of the Midra Member were not indicated by the Gamma log through the increasing activity towards the base of the Rus Formation and the abrupt decline to very low values at the top of the Umm er Radhuma records the changes in lithology and the passage from dry Rus to the aquifer below.

Project Borehole Geophysical Profile





hole Geophysical
Borehole No. P22a
S. P. Log
mv
Gamma Ray Log
cps
Litho Log
Formt'n
ti ty Log
ohm m^{2}m
▼32
64"
16"
115
Base of Fresh water
150.9
100
150
0
20
40
60
80
100
Simsima Member
Upper Rus Formn
Lower Rus Formn
Umm er Radhuma Formn.
Marly Lst.
Dol. Lst.
Chalky Lst
Dolomite
Chert
Gypsum

Fig. 7.10

Pr ject Borehole Geophysical Profile