BRITISH GEOLOGICAL SURVEY
-3 JUL 1998
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HYDROGEOLOGY OF THE KUFRA AND SIRTE BASINS,
EASTERN LIBYA.

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by

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List of Figures.

INTRODUCTION

The Sirte and Kufra basins extend over the greater part of eastern Libya (Figure 1) and have been sites of major sedimentary deposition from Palaeozoic to Recent times. The upper horizons in each are coincident with regional fresh groundwater systems which however appear largely independent. The Kufra basin system discharge into the Nubian basin of Egypt and the Sudan (Shatta, this volume). The Sirte basin system terminates against the Mediterranean and the Jebel Akhdar uplift and discharges into coastal and inland sabkhats extending eastwards from the Gulf of Sirte to the Qattara Depression. All dated groundwaters are fossil ranging from 40,000 to 5,000 years BP. Some current recharge undoubtedly occurs, mostly via run-off from the peripheral foothills of the adjacent highland areas of the Tibesti and the Haruj Al Aswad, but no adequate evaluation has yet been made and its significance is speculative. The thickness of the potentially productive fresh water zones in both basins approaches 1000 m. Total volumes of water in storage are very large and must be of the order of several thousand billion (10^9) m^3. Development is limited by logistical constraints in these remote regions but major agricultural irrigation schemes are current in both basins.

Subsurface information on the Kufra basin is available mainly from the results of well drilling in association with the Kufra Agricultural Development Scheme and by extrapolation of surface outcrop features. Summary data on the Kufra well fields have been published by Ahmad (1980) and Pallas (1981). The information presented here on the Sirte basin is derived almost wholly from studies carried out by a team from the Institute of Geological Sciences between 1967 and 1974. An initial hydrogeological appraisal was reported on in the first Symposium on the Geology of Libya (Wright and Edmunds, 1971).

In 1971, the Institute commenced more detailed investigations in two specific areas (Phase 1 and Phase 2 areas, Figure 2) together extending to some 76,000 sq km where the combination of good water quality and terrain and soil character indicated a potential for development. The results of these studies are embodied in a series of unpublished reports and in three publications dealing with specific aspects (Edmunds and Wright, 1979; Edmunds, 1981; Benfield and Wright, 1981).

PHYSIOGRAPHY

The region is desert, with an average annual rainfall mainly below 25 mm (Figure 2 and Table 1). The precipitation is highest in the northern coastal region and in the Tibesti-Ennedi Highlands which border the Kufra basin to the south. Records are of short duration and lack information on intensity rates. Precipitation occurs mainly in the winter months between November and February but summer storms also occur in the Tibesti region from monsoonal winds.

TABLE 1. Rainfall Records in Eastern Libya.

Location	Average Annual Precipitation (millimetres)	Records (years)
Ajdābiyā	129.0	17
Marsa El Brega	122.0	9
Al Jaghbūb	9.7	12
Maradah	15.8	10
Jālū	12.7	8
Tāzirbū	2.9	10
Kufra	1.3	17
Zouar (Tibesti Region)	31.0	6

The average number of days per annum with rain varied from less than one at Kufra to 24 at Marsa El Brega. Studies (Hazen and Sawyer, 1960) of Saharan rainfall records have shown that deduced rainfall intensities of individual storms tend to be comparable and differences in annual rainfall relate to the frequencies of storms.

The surface cover of sand, gravel or rock is largely devoid of vegetation except along the more prominent wadis, and in the vicinity of the scattered inland oases which owe their existence to shallow groundwater. Dominant physiographic features are the great Rabyānah and Calanscio sand seas, constituted of a complex of mainly longitudinal dunes elongated in a general north-south direction. Elsewhere extensive areas are covered by flat or gently undulating plains of coarse sand or gravel which have the local name of sarir. Rock outcrops occur mainly along the western margins of the Sirte basin, including Jebel Zelten and the Haruj al Aswad, and more extensively around the Kufra basin. The general land elevation rises inland from the coast to 400 m above sea level at Kufra, and to 1000 m in the Haruj and in the Tibesti foothills. Drainage patterns are mostly apparent in the marginal piedmont areas or on rocky plains and are largely absent in the sarir plains and sand seas. In various places, dune sands have clearly encroached on older drainage lines.

GEOLOGY

Regional Setting.

The sedimentary successions of the Kufra and Sirte basins (Figure 1) were deposited on the sinking foreland between the ancient African cratonic shield and the mobile Tethys belt (Klitzch, 1971). Active deposition in association with subsidence occurred in the Kufra basin throughout most of the Palaeozoic and Mesozoic and in the Sirte basin from the Late Mesozoic to the Late Tertiary and possibly Quaternary.

The sediments of the Kufra basin are mainly sandstones and shales, continental or marginally marine in origin which developed in relation to alternating troughs and uplifts controlled by epeirogenic movements and accompanied by some block faulting. The main marine incursions occurred in the Silurian and early Devonian. Following Hercynian movements, the Palaeozoic formations were eroded from uplifted areas and re-deposited in adjacent lowlands, notably the Kufra basin between the Tibesti-Sirte and Ennedi-Uweinat uplifts. The Carboniferous sediments of the basin are mainly continental in origin since by that time access to the Tethyan sea had become restricted. Sediments of Triassic and Jurassic age are thought to be absent and the overlying 'Nubian' is continental and probably in the main of Lower Cretaceous age.

The Sirte basin was initiated in late Cretaceous times by collapse of the eroded Tibesti-Sirte uplift into a series of horsts and grabens. Subsidence continued but with decreasing intensity, possibly to Quaternary times. Initially, the environment was mainly marine but with increasing lagoonal and continental facies developing in middle to late Tertiary times. Early sedimentation was complex with deposition of shales in the grabens and carbonates on the horst blocks but the later Cretaceous sedimentation became more uniformly argillaceous. The lower Tertiary formations (Palaeocene and Eocene) include thick and extensive carbonates and shales. At this time a major marine transgression extended southwards from the main basin into a deep embayment reaching the Tibesti region and possibly beyond (Desio, 1971). The Post-Eocene sequence includes sands, sandstones, clays and carbonates deposited in a period of general regression which commenced with the onset of the Oligocene.

Stratigraphy.

Kufra Basin: Comparatively little stratigraphic data has been published and the writers of this paper have little first hand knowledge. Information mainly exists in the unpublished reports of oil companies mostly relating to surface surveys, and of consultants concerned with groundwater development in the Al-Kufra area. The most detailed review of consultants data is given by Pallas (1981).

Table 2 shows the general succession in the Kufra basin and Figure 3 a schematic cross-section from the Uweinat massif across the Kufra and Sirte basins to the Jebel Akhdar. Palaeozoic formations outcrop against the Uweinat massif and on the northern and western margins of the Kufra basin where they form a series of inward dipping cuesta-like ridges. A gap in the latter occurs at Rabyānah and borehole data show that the Palaeozoic rocks are overlain by thin continental Mesozoic sandstones thought to be continuous with the Nubian Series and by the feather edge of the overlying marine Upper Cretaceous shales, both extending south from the Sirte Basin. The Nubian Sandstone Series is disconformable with the underlying Palaeozoic strata in the centre of the Kufra basin and unconformable and overlapping in the marginal areas. It is largely unfossiliferous other than for obscure trace fossils, plant remains and fresh water gastropod shells, none of which closely delimit the age of the Series and it could conceivably range from upper Palaeozoic to upper Cretaceous although it is generally considered to be mainly lower Cretaceous. Stratigraphic dips in outcrops in the centre of the basin are negligible and only increase to a few degrees in marginal areas adjacent to Palaeozoic outcrops, (Fisk and

TABLE 2

GEOLOGICAL SUCCESSION IN THE KUFRA BASIN

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

Pennington, 1971) reflecting the stability of the basin during post Nubian times. Other than Quaternary surface sands, gravels, caliches, lake sediments etc., no formations of Post Nubian age have been recorded and the area seems likely to have been a source for terrigenous material for the Sirte basin Tertiary sediments.

Sirte Basin: Considerably more information is available on this basin due largely to extensive oil exploration. Table 3 shows the full sequence in the southern Sirte basin and Table 4 gives a more detailed description of the Post-Eocene which is of most interest in a hydrogeological context.

The Palaeozoic formations are mainly quartzitic sandstones which form thin residuals overlying the uplifted and eroded basement areas but increase in thickness away from them. The Mesozoic continental sandstones may range in age from upper Jurassic to lower Cretaceous and have been subjected to several periods of erosion, chemical weathering and some reworking. They are assumed to be contemporaneous with the Nubian Series of the Kufra basin. They are generally unfossiliferous but angiosperm pollen have been identified in one area at a low level in the sequence which date them as not older than Albian (Gillespie and Sandford). The overlying marine upper Cretaceous comprises mostly shales which in common with the later Tertiary formations thicken towards the north-south axial zone of the Sirte basin.

The early Tertiary (Palaeocene and Eocene) formations are regionally extensive marine carbonates with subordinate shales which present a marked lithological contrast to the underlying Mesozoic formations. During this time, the seas transgressed deep into the Tibesti embayment and the Tertiary sediments exhibit overlap onto older Palaeozoic rocks.

The results of the extensive studies of the Post-Eocene sequence by IGS have been given in an earlier publication (Benfield and Wright, 1981) of which the following is a summary. Four stratigraphic units have been recognised (Table 4) with combined thicknesses which range from less than 300 m to more than 1500 m and increase towards a number of troughs of similar alignment within a main north-south trending axial region (Figure 4). The same structural controls are generally apparent in the isopach patterns of the lower three units and indeed the general ground surface contours (Figure 2) reflect a similar pattern which may indicate that consistent downwarping has continued until comparatively recent times.

Oligocene sediments are dominantly marine comprising calcareous sands and sandstones with clays and carbonates which increase in importance northwards (Figure 6). The succeeding Marada Formation of Lower and Middle Miocene age shows a similar pattern of facies change. Sands of probable fluvial origin dominate to the south-west. To the north, individual sand bodies interfingering with clays, commonly evaporitic, and carbonates and representing deposition in transitional environments, ultimately die out within marine carbonates and clays. In both the Oligocene and Lower and Middle Miocene, lithofacies and thickness variations have been related to shoreline trends and the locations of major zones of subsidence and to linear trends of increasing sand input.

TABLE 3

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

Era	AGE	FORMATION	THICKNESS (general range in metres)	LITHOLOGY
TERTIARY - QUATERNARY	Recent	-	0 - 100	Windblown sands, calcretes, fossil soils
	(iii) Post-Middle Miocene (PMM)	Calanscio		
	(ii) Lower and Middle Miocene (LMM)	Marada	150 - 900	Mainly unconsolidated sands interbedded with clays and more locally calcareous sandstones grading to sandy carbonates
	(i) Oligocene	-		
	(iii) Upper Eocene	-	60 - 120	Limestone and dolomites, some marls and shales
	(ii) Middle Eocene	-	210 - 330	Nummulitic and argillaceous limestones, some marls and calcareous sandstones
	(i) Lower Eocene	-	240 - 490	Interbedded dolomites and anhydrites
	Palaeocene	-	150 - 610	Carbonates and some shales
UPPER MESOZOIC	Upper Cretaceous	(ii) U Cretaceous Shales	20 - 460	Marine shales
		(i) Transgressive Series		Anhydritic shales and some sandstones
			Post Nubian Unconformity	
	Continental Mesozoic (=? Nubian)	Sarir or Basal Sandstones	0 - 760	Sands and sandstones, sometimes shaly and locally interbedded with shales and sandy mudstones and siltstones
			Hercynian Unconformity	
PALAEOZOIC	Undifferentiated Palaeozoics	-	0 - 140	Quartzite sandstones, siltstones and micaceous shales
			Caledonian Unconformity	
	Cambro-Ordovician	Gargaf Group	0 -1160	Quartzites and quartzitic sandstones
	Pre-Cambrian	-	-	Folded metamorphic and mainly granitic igneous rocks

TABLE 4

POST-EOCENE SEQUENCE OF THE SIRTE BASIN.

Age	Formation Name	Lithology	Thickness Range in metres
Holocene/ Pleistocene		Surface sands, gravels and calcretes	0 - 30
Post-Middle Miocene	Calanscio Formation	Medium to coarse-grained sands, grading to calcareous sandstones in part, with thin inpersistent clay interbeds.	0 - 210
Lower and Middle Miocene	Marada Formation	In north: marine carbonates and clays with evaporites. In an intermediate north-west to south-east zone: interbedded clays, carbonates, sands and sandstones of shoreline complex. In south west and south: fluvial sands and sandstones with thin clays.	150 - 880
Oligocene	-	Non-Marine Facies: coarse-grained sands and sandstones with interbedded clays; restricted to the south west and south. Marine Facies: glauconitic calcareous sandstones, limestones, dolomites and clays with some evaporites; makes up the bulk of the Oligocene.	240 - 730

A major regression took place in Middle Miocene times and the succeeding Calanscio Formation rests on a marked erosion surface. It comprises up to 210 m of often coarse fluviatile sands with thin, impersistent clays and in comparison with the two underlying units has a restricted occurrence within the central axial region of the Sirte basin (Figures 4 and 5). The Formation is unfossiliferous and its age can only be designated as Post-Middle Miocene. However it seems likely that sedimentation commenced in the early Pliocene following the major late Miocene (Messinian) fall in Mediterranean sea level and its subsequent rise at this time. The close relation of broad depressions in the basal surface of the Formation with long-established structural lows suggests downwarping over a long period and deposition may well have continued throughout the Pliocene and into Quaternary times.

The relations between the Calanscio Formation and the thinner Garet Ueda Formation (Di Cesare et al., 1963) which has a restricted occurrence north of the Calanscio sand sea is discussed in some detail in Benfield and Wright (op.cit). The Garet Ueda Formation overlies an eroded surface in Miocene rocks and is regarded by Di Cesare et al. (op.cit) as being of Quaternary age. It comprises a series of alteranting aeolian and lacustrine formations, the lowest of the latter grading southwards into fluviatile sediments.

Due to the paucity of data a close correlation of the Calanscio and Garet Ueda Formations has not been attempted. However during the IGS studies in the Sirte basin, the grain size frequency distribution of numerous samples of the Calanscio Formation were analysed by the method of Moiola and Weser (1968) and without exception indicated a fluviatile origin. Associated clays are interpreted as overbank deposits and occasional thin limestones as of lacustrine origin. Unfortunately no samples were collected in the unsaturated zone of the Calanscio Formation which is up to 40 m thick and the possibility of aeolian-lacustrine cycles occurring in this upper section cannot be discounted. Clearly however the bulk of the Calanscio Formation is primarily fluviatile and a correlation with the basal fluviatile horizon of the Garet Ueda seems possible. Significant thickness reduction in the Calanscio Formation is known to occur northwards and the feature could well be a primary depositional change (Figure 6).

Geomorphological Evolution.

The main source of sediment supply for the Sirte basin was the higher lands to the south and west where Mesozoic and Palaeozoic rocks have been continuously exposed since Cretaceous times. The geomorphological history of the region has yet to be evaluated adequately but it seems probable that the transection of the main interior plain (now at some 400 to 500 metres elevation) within the Kufra basin occurred in Oligocene to Miocene times and was contemporary with the deposition of the bulk of the sediments in the subsiding Sirte basin to the north. Residuals of the widespread African surface (King, 1962) of Late Cretaceous to Eocene age may also be represented by the accordant levels of the residual flat topped hills around 600 to 700 metres elevation in the interior of the Kufra basin and doubtless represented also in the peripheral highlands. Sediments of this period in the Sirte basin are mainly shales or carbonates and terrigenous influx must have been comparatively slight. During this period of relatively stable conditions the African surface would have developed widespread and uniform planation on adjacent exposed land masses.

A significant change occurred at the commencement of the Oligocene with probable uplift to the south causing a northward retreat of the sea. There was uplift also in Oligocene times in the Haruj region to the west. During Oligocene and Lower and Middle Miocene times, periods of transgression and regression alternated with corresponding gradations from continental fluviatile sediments in the south via shore line complexes to wholly marine sequences in the north.

A major regression of the sea occurred in Post-Middle Miocene times and this seems likely to have been due to a significant and rapid fall in the level of the Mediterranean (Barr and Walker, 1973). Transgression occurred in Pliocene times and marine sediments of this age occur in coastal Libya close to the Gulf of Sirte. The rate of sea level rise appears to have been rapid as narrow erosional channels cut during the intervening period have been preserved and filled with sediments of fluvial and, to the north, probably estuarine origin. These represent the earliest sediments of Post-Middle Miocene times and appear to be overlain by the dominantly fluvial Calanscio Formation. The Formation overlies a dissected surface and it is likely that erosion both prior to and contemporaneously with its deposition in the central basin occurred in marginal areas stripping off older Miocene and Oligocene rocks. The land surface developed as an aggradational pediplain within the basin succeeded westwards by an erosional pediplain of late Tertiary to Quaternary age. The surface has been modified and regraded by late Pleistocene and Holocene cycles which included significant arid phases.

HYDROGEOLOGY

Regional Occurrence.

Important fresh water aquifers constituting regional groundwater systems occur within the Nubian Sandstone Series of the Kufra basin and the arenaceous formations of the Post Eocene of the central Sirte basin. Fresh water may also occur in the older Palaeozoic sandstones which underlie the Nubian and also outcrop on the south-east margins of the Sirte basin but definite information is lacking and sandstones of this age elsewhere in North Africa are generally of low permeability. The Nubian and Post Eocene aquifers occur interbedded with clays or shales and respond to abstraction in complex fashion, either unconfined or leaky to artesian. Under natural flow regimes, shallow gradients predominate and vertical head differentials are not significant except in the north of the Sirte basin (Figure 7). The two systems appear largely independent although some interaction may occur in the vicinity of Rabyānah the significance of which is discussed later.

Nubian Sandstone Aquifer.

The main occurrence is within the Kufra basin where thicknesses of up to 1000 m containing fresh water have been recorded in the vicinity of the Kufra oasis. Continental Mesozoic sandstones equivalent to the Nubian extend beneath the Tertiary sequence of the Sirte basin. Recorded thicknesses of the continental Mesozoic sandstones are variable, generally less than 300 m and wedging out occurs over elevated basement areas.

Figure 7 shows piezometric surfaces in both the Nubian and Post-Eocene aquifer systems. Control points in the Nubian are few and those within the continental Mesozoic sandstones, though more frequent, are derived from drill stem tests in which observed water level elevations have been converted to equivalent fresh water heads. To the north of latitude 27°00, the ion concentration in the groundwater is frequently in excess of 100,000 ppm and the density correction is large. To the south of this latitude, the water is relatively fresh and the correction is negligible. The distribution of head levels shows some anomalies but is reasonably consistent to the south of latitude 28°00 indicating probable hydraulic continuity. (In contrast, data from areas farther north exhibit irregular values suggestive of discontinuity presumably due to wedging out or faulting). The presence of fresh water within this deep artesian aquifer almost certainly indicates flushing in relatively recent times and confirms continuity with the Nubian outcrop occurrence. Although the piezometric contour trend in the deep aquifer cannot be regarded as very accurate, it suggests a throughflow eastwards to join the Nubian artesian aquifer system in Egypt (Figure 1).

Under natural flow conditions, some small discharge is occurring at Kufra and the other oases in the northern Kufra basin. The upward component of flow is quite small and decreases rapidly away from these discharge areas. The main gradients are flat lying (c. 1:3000) and diverge around the pre-Cretaceous formations outcrop which are likely to have low to negligible permeability. The northerly flow path seems likely to relate in the main to throughflow within the Mesozoic sandstone aquifer below the Sirte basin and possibly also to outflow into the overlapping Post-Eocene sequence as indicated by the convergent head levels.

Transmissivities in the Nubian aquifer are known only in the vicinity of the Kufra oasis where according to Ahmad (1980) the tests with wells to depths of 300 m gave transmissivity values in the range 200-700 m^2/day and with wells to depths of 500 m, the range was from 1700-3800 m^2/day. A small upward gradient is said to exist. Assuming regional consistency in these latter values and a gradient at the northern and north-eastern margins of the basin of 1:3000, an outflow of between 6.6 and 14.75 litres/sec/km is indicated. Total discharge is assumed to be effected to the north of the Uweinat massif (Figure 19 in Pallas, 1981) and along the 350 km front so indicated a total annual outflow of between 70 and 160 M m^3 is estimated.

Post Eocene Aquifer of the Sirte Basin.

Significant detail is available on the hydrogeology of the Post-Eocene multi-aquifer which indicates that it constitutes a major unified flow system of regional extent. Important controls include (i) discharge elevations at or below sea level in a low lying sabkhat area between the Gulf of Sirte and the Qattara Depression and south of the Jebel Akhdar ridge and (ii) the occurrence of recharge during previous pluvial periods. The possibility of current recharge either by direct precipitation, run-off from marginal highlands or by leakage from the subjacent Nubian aquifer where the Kufra and Sirte basins overlap is speculative.

The Post-Eocene aquifer system is essentially unconfined to semi-artesian in the predominantly sand and clay sequence of the southern Sirte basin. Groundwater flow is effectively horizontal with negligible vertical hydraulic head differentials. Farther north where clays and carbonates increase in amount, the deeper horizons become wholly artesian and exhibit marked upward head gradients. The feature can be attributed to restricted discharge in the less permeable deeper horizons. The Post Eocene aquifer contains fresh water throughout the south of the Sirte basin becoming brackish to saline in the north, particularly in the deeper levels which have increasing clays, carbonates and evaporites. The water table is at or below sea level in the vicinity of the discharge zone along the eastern Gulf of Sirte and further east to Al Jaghbūb and rises to some 200 metres above sea level 600 km to the south. Excluding the sabkhat discharge areas, depths to the water table are least in the central topographic depression (Figure 2) where it may be as shallow as 7-14 metres, for example near Jalū and Tāzirbū, increasing to more than 250 metres in the marginal uplands. Hydrogeological information on the underlying Eocene and Palaeocene is scanty but indicates the presence of saline water and low permeabilities in the mainly carbonate formations.

Regional flow patterns.

The piezometric surfaces map (Figure 7) is based mainly on observed water levels in wells drilled and completed down to some 100 m below the water table. The older stratigraphic units (Lower and Middle Miocene; Oligocene) are exposed on the western side of the basin (Figures 4 and 6) and the location and dip of the formation boundaries must be taken account of in the interpretation of observed well water levels. To the south of latitude 28°00 where the entire Post-Eocene sequence is mostly sand with variably interbedded clays, sufficient data is available to demonstrate the general accordance of hydraulic head levels in the Post-Middle Miocene (PMM) and the deeper Lower and Middle Miocene (LMM) aquifers. The information derives from the deep wells drilled for irrigation purposes in the Sarir area and the accordance observed seems likely to persist westwards where interbedded clays reduce in amount. In a deep well drilled for hydrogeological exploration purposes to the base of the Oligocene at Q1-65, (28°00N;21°00E approx.) only a slight rise in head levels was apparent in the deeper Oligocene at some 600 to 900 metres below ground level. To the north of latitude 28°00, a significant head differential is developed between the mainly sand aquifer of the PMM and the aquifers within the subjacent LMM and Oligocene which include significant and increasing carbonate and shale components. Detailed information on relative piezometric heads is largely limited to the Phase 1 area and in Figure 7 is shown the individual contour surfaces for the two aquifers. Positive upward differentials appear highest in the western boundary area where they may attain 38 m. Measurements in the deeper Oligocene are few and often suspect but some show higher head values than in both the overlying LMM and PMM.

Some qualitative deductions on recharge can be made from the piezometric contour maps. More quantitative evaluations will follow the discussion on aquifer parameters. The general direction of flow is northwards to the main discharge areas in the low lying zone of sabkhats along the

Gulf of Sirte and eastwards to Qattara. Other discharge areas of smaller significance are the oases of Awjilah-Jālū and Tāzirbū. Some recharge by direct precipitation is probable but it must be of small or negligible proportions. The general trend of the piezometric contours is fairly regular. An exception is the marked curvature of the contours on the western margins of the basin which can reasonably be attributed to recharge of run-off from the adjacent highland areas of the Haruj al Aswad and the Tibesti. Well marked drainage networks extend from the Haruj and to a lesser extent across the Tibesti sarir. A possibility exists that the contour trends are transient features related to recharge in a recent pluvial period. Although this cannot be discounted, a consideration of possible run-off rates in these highland areas suggests that current recharge could account for the marked curvature of the piezometric contours.

The piezometric contour trends and elevations in the southern and south-eastern marginal areas indicate two contrasting conditions. To the south near Rabyānah, there seems a probability of recharge from the Nubian into the Post-Eocene by lateral inflow and alternatively or additionally by upward leakage. The possibility is indicated by the converging head levels within the two aquifers and by the thinning and wedging out of the intervening early Tertiary formations. Further north, although an increasing upward head differential develops between the Nubian and Post-Eocene, the presence of Eocene and Palaeocene carbonates, shales and evaporites thickening in that direction reduce the likelihood of significant leakage occurring.

In the south-east of the Sirte basin, the trend of the piezometric contours towards the outcrop of pre-Cretaceous formations indicates lack of recharge, whether by rainfall, run-off or groundwater inflow. The rainfall of the region is very low (Tāzirbū and Kufra records, Table 1), and it seems unlikely that the low elevation of the hills bordering the Kufra basin to the north would attract orographic effects. Run-off can also be discounted by the common occurrence of sand dunes across the wadi outlets debouching onto the plains. The main formations which abut against the Post-Eocene sequence are Palaeozoic sandstones which have generally a low permeability.

Aquifer Parameters.

The fundamental aquifer parameters of transmissivity and specific yield/storativity are needed for the evaluation of the water resources of an aquifer and its development planning. The most reliable method, by pumping test analysis, is costly and in the case of a thick, multiaquifer sequence such as occurs in the Post-Eocene of the Sirte basin presents considerable problems of interpretation in consequence of the practical limitation of the test procedures. These limitations include (i) partial penetration effects consequential on the need to case out the higher levels to allow for drawdown and pump installation and the economic restraint on drilling in excess of probable requirements, and (ii) the short duration of the tests (which accentuate partial penetration effects) and commonly preclude obtaining information on specific yield. Detailed aquifer testing by this method over this large region was necessarily limited to selected areas (Phase 1 and Phase 2) where the combination of terrain suitability for irrigation and the available water quality had indicated a likely potential for development.

In the Phase 1 area (Figure 2) the Post-Middle Miocene constitutes the aquifer of main significance. Water quality considerations impose limitations on potential in the eastern Phase 1 area and north of 29°00N, and similar considerations together with generally lower permeability and poor terrain characteristics precluded initial consideration of the LMM and Oligocene to the west (or below). The PMM aquifer in the selected area has a saturated thickness in the range 75-140 m and a number of exploration-production wells were drilled to its base and screened from approximately 30 m below the water table to total depth. Short duration pumping tests of 5 to 10 days, demonstrated artesian to leaky artesian responses which gave transmissivity values for the main responding layer between significant clay layers and opposite the screened interval. The transmissivity of the overlying saturated section was determined by size analysis of sample of the unconsolidated sands. The method employed plots the D50 size against dispersion and is described by Masch and Denny (1966). Sampling was careful and continuous in order to obtain all representative material above the silt grade and a comparison of the results obtained over the pump tested interval by the two methods gave confidence in the analysis. A modelling technique was subsequently applied to individual tests using the various computed grain size values throughout the sequence and provided additional confirmation. The latter technique was also able to indicate specific yield for these cases where drawdown occurred at the water table but the sensitivity was inevitably low. For the purpose of well field design predictions, conservative values of specific yield were assumed. The general transmissivities of the tested PMM aquifer in the Phase 1 area were in the range 750-1500 m^2/day.

In the Phase 2 area, aquifer analysis proved more difficult due to the requirement to develop the Lower and Middle Miocene in addition to the Post-Middle Miocene and the greater heterogeneity of the combined sequence which includes, sands, clays, sandstones and some carbonates. Various techniques were applied to resolve the problems arising mainly from partial penetration and lateral anisotropy including grain size analysis, geophysical log interpretation of porosity, production logging and modelling. Subsequent drilling of large numbers of irrigation wells in this area (Ahmad, 1980) demonstrated a wide range of transmissivity values (determined by one day tests). In an area some 40 km square, a main range of values between 300-1300 m^2/day occurred in some 70 wells screened from 150-300 metres and therefore largely in the LMM. In addition a narrow belt between 1-5 km across was discovered and traced for 40 km with transmissivities in the range 4000-10,000 m^2/day, and occurring in a gravel facies. The stratigraphy is not described but it seems likely that the gravels must form a basal facies in the PMM developed in narrow valleys eroded on the LMM surface following the major sea level fall in Middle Miocene times. The discovery of the so-called Sarir channel could have important implications on groundwater resource development if they should prove to be of common occurrence in the southern Sirte basin.

The multiaquifer occurrence within the Post-Eocene sequence of the Phase 2 area of the Sirte basin has demonstrably a wide range in transmissivity although the frequency and extent of similar features to the so-called Sarir channel are as yet unknown. There is however some justification for the recognition of a major hydraulic boundary in the central axial region at the top of the main clay layer within the LMM at approximately

300 m below ground level (Figure 6). Flow net analysis has been applied to this unit using transmissivities derived from pumping tests etc. on the five exploration sites spaced along a north-south section through the Phase 2 area. The transmissivities show an increasing trend from south to north (600 m^2/day to 1500 m^2/day. Although not too much reliance can be placed on the analysis (which exclude consideration of the local 'channel' occurrence) they do indicate the likelihood of no recharge by vertical infiltration (see discussion below).

Groundwater Chemistry.

The regional water quality distribution can be described using the contoured total mineralisation map (Figure 8). At Kufra oasis and throughout much of the Kufra basin the total mineralisation in the Nubian Sandstone aquifer is exceptionally low, typically below 100 mgl^{-1}; at Kufra oasis this water has been proved to depths of 900 m below ground level; the only deterioration occurs at shallow level near the oases of Kufra, Rabyānah and Bzema due to evapotranspiration. To the north of Kufra, data are limited but it is likely that salinities of < 1000 mgl^{-1} persist at least to the latitude of Tāzirbū As the Nubian aquifer becomes wholly confined beneath the Sirte basin progressive quality deterioration is observed; at the latitude of Sarir, brines with total mineralisation of 100-180 gml^{-1} are found, indicating that no significant flux of water from south to north has occurred, probably since deposition; as noted above however there is a probable zone of less saline water to the south and east suggesting possible throughflow.

In the Sirte basin, the contours are drawn for the two principal aquifers within the PMM and LMM; the waters of the Oligocene and deeper aquifers north of 28°N and beneath the LMM are relatively saline (8-12 gml^{-1}) and, although unimportant for water supply, they are exploited for oilfield injection. The unconfined Oligocene in the south and west of the Sirte basin does however contain signficant volumes of fresh groundwater.

A significant volume of the resources in the Sirte basin south of 28°N are below 2000 mgl^{-1} total salinity, and there is a prominent fresh water lobe which extends further north towards the coast, between 20° and 22°E. North of 29°20' there is a marked increase in salinity which is related both to the marine character of the LMM aquifer and to the mixing by lateral recharge of the LMM by the much attenuated PMM. To the south east of Jalo, the contours are cross-cut obliquely by a NW-SW trending fresh water 'channel' with water less than 500 mgl^{-1}, which is considered to represent recharge from a former wadi during the Holocene and has been described elsewhere (Edmunds and Wright, 1979).

The main differences in major element chemistry within both basins are given in Figure 9, which is a summary of several hundred analyses. The very low salinity groundwaters at Kufra and in other oases and wells in the basin have a distinctive composition over a saturated thickness of several hundred metres. As the water in the Kufra basin becomes saline beneath the Sirte basin, the m Mg/Ca ratio remains constant at 0.5. The distinctive chemistry and salinity has been used to distinguish possible upward leakage into the Sirte basin; this is indicated at two localities between 26° and 27°N.

The Oligocene, LMM and PMM aquifers of the Sirte basin may sometimes be distinguished chemically. The Oligocene sequence was sampled vertically in the south western Sirte basin and found to have a relatively constant low mineralisation (1100-1500 mg/l) through the 700 m saturated thickness, with a characteristic ionic composition. Northwards as the groundwater in the Oligocene becomes saline (5000-7000 mg/l) the ionic composition shows a decrease in m Mg/Ca ratio and an increase in SO_4 in consequence of the dissolution of gypsum or anhydrite.

Almost all groundwaters pumped from the water table PMM aquifer have a restricted composition on the trilinear diagram, even though the mineralisation increases from < 1000 to ≥ 2000 mg/l along flow lines between 27°-29°N. This widespread chemical homogeneity throughout a very large saturated thickness suggests that overall hydraulic continuity exists despite the common occurrence of interbedded clays; no sulphate increase is noticed, nor any indication of influence by marine lithologies. The evidence is consistent with water movement through a uniform sequence of fluvial deposits. An important exception to this uniformity lies in the salinity increase (essentially an increase in the Cl/SO_4 ratio to the east and south of Jālū and Awjilah oases. The reasons for this region of saline groundwater are considered to result from evapotranspiration during the Holocene and late Pleistocene. This area coincides almost exactly with the topographic low and represents the area where the chemistry has been modified by successive changes in the shallow water table, with loss of SO_4 by gypsum precipitation (Figure 9). The groundwaters in the fresh water 'channel' S E of Jālū are seen to be of different ionic composition to those in surrounding PMM aquifer.

In contrast, groundwaters in the underlying LMM have a much more variable hydrogeochemistry reflecting the transition between continental and marine lithologies; the geochemical characteristics can be used to support the hydraulic conclusions that in the north of the area the LMM and PMM are separate aquifers and that leakage from LMM to PMM does not take place except perhaps on a very small scale. The Sr/Ca ratio in the LMM groundwater increases dramatically from < 0.2 to > 10 mg/l across the continental/marine boundary. This effect has been discussed in Edmunds (1981) where the LMM/PMM relationship is also considered in more detail.

Therefore the present-day water quality distribution and chemical characteristics have been shaped by four important factors:

(i) lithological controls - especially the continental or marine nature of the sediments, important in restricting the large scale occurrence of fresh water to the south of 28°N.

(ii) topography - which has allowed the fresh water lobe to develop to the west of Jalu yet has been the prime cause of water quality deterioration to the south, east and north of Jalu.

(iii) mixing and leakage - which has produced modification at the boundaries between the aquifer units of both basins.

(iv) palaeohydrology - which has maintained the gradient of fresh water recharge from south to north (Tibesti) and also from the west (Haruj al Aswad) and has given rise to late, superimposed features such as the main fresh water channel.

Groundwater Age Relationships.

Stable and radioisotope measurements have been carried out on pumped groundwater samples from a selection of wells in the Sirte and Kufra basins (Figure 8 and Table 5) and the results used to obtain information on ages and conditions of recharge. A fuller discussion of the data including the derivation of the radiocarbon ages is given in an earlier paper (Edmunds and Wright, 1979). The samples were taken from wells screened in the main phreatic PMM and Nubian aquifers and mostly collected during short (5 to 10 days) pumping tests. The ages obtained may represent a blend of waters from the water table to at least the lower screen setting.

Table 5. Groundwater Ages from wells in Kufra and Sirte basins.

Location	Number of Samples	Age Range (years BP)	Screen Range (m below water table)	Aquifer
Kufra Oasis	6	33000-24000	100-340	Nubian
Southern Sirte Basin	3	34000-28000	63-129	PMM/subordinate LMM
Northern Phase 1	1	31000	44-?	
Central Phase 1	5	24000-14000	25-103	PMM
Eastern Phase 1	1	8000-5000	74-94	PMM
	3	8000-5000	2-4	PMM

The oldest waters occur at Kufra oasis, from three widely spaced wells in the southern Sirte basin and in one well in the northern Phase 1 area. The wells of intermediate age in the central Phase 1 area are also widely spaced. They occur downgradient of the wells in the southern Sirte basin although not on the same flow line. A possible explanation is that the younger group are closer to a source of more recent recharge which has flushed out older waters by lateral displacement. Using a permeability of 15 m/day which is typical of the unconsolidated sands of the PMM and LMM aquifers and the present piezometric gradients, piedmont recharge from run-off in the Haruj foothills could have travelled some 250 km in 24000 years along a suitable flow line and displaced older waters en route.

The youngest groundwaters occur in channels of fresher water surrounded by more mineralised and probably older groundwater. Although there are no indications of a topographic valley form above the channel, it was concluded (Edmunds and Wright, 1979) that derivation by vertical recharge from a fossil wadi was the most likely explanation and various confirmatory evidence exists. The channel continues the trend of a visible valley (Wadi Behar Belama) some distance to the south west and which has associated gravels with material derived from the Tibesti mountains. Dated material includes mammalian bones of 4,000-300 years BP and wood fragments from adjacent pre-historic sites of 8,000-7,000 years BP (Pachur, 1980)

The alternative concept of rapid groundwater flow through highly permeable material is more speculative. Groundwater travel to the central Sirte basin within the observed age span would require aquifer permeability of some 100 m/day for the corresponding gradients present. Permeabilities of this order have been encountered in the so-called Sarir channel discussed above which since it contains gravels which include Tibesti rocks could extend back to this mountain area and a suitable source of recharge. There is however no evidence that a basal channel is coincident with the observed fresh water feature. Thus although both explanations must be considered possible, derivation by direct recharge from a fossil wadi seems more probable in the present instance. Further studies on fresh water zones and sedimentary channel features are clearly desirable since their occurrence could have important implications in a water resource context.

RECHARGE AND RECHARGE CHRONOLOGY

A discussion on recharge rates and conditions must relate not only to the current arid period but also to previous climatic conditions in the Late Pleistocene and Holocene. Present rainfall over east-central Libya is probably less than 25 mm annually (Table 1). Some recharge by direct precipitation is possible, nonetheless. Favourable circumstances include the flat terrain largely devoid of vegetation, high infiltration capacity of the loose surface sands and gravels and the high intensity of storm rainfall occurrence which falls in the winter months when evapotranspiration rates are low. The most critical additional factor determining recharge is the moisture deficits in the surface sands. Information on moisture profiles in this environment is scanty but it is commonly assumed that deficits will occur mainly through water movement in the vapour phase and this could therefore be quite small. Gupta (1979), measured seasonal moisture distributions under arid conditions (in weight percentages) within an unstabilised sand dune devoid of vegetation. Converting his data to volume percentages (by making assumptions on bulk density), a maximum soil moisture deficit of some 18 mm develops in the top 9 metres overlying sand at field capacity. Deficits of this amount although quite small would effectively preclude recharge with low annual rainfall of comparable order. Dincer et al. (1974) calculated a recharge rate equivalent to some 3 mm/a, through aeolian dunes in eastern Saudi Arabia receiving 80 mm/a. Pachur (1980) with theoretical calculations obtained a recharge of either 50% or 25% from a typical arid zone precipitation pattern of c. 100 mm, the alternative values depending on whether the rainfall was summer or winter. No soil moisture deficits appear to have been assumed.

No measurements or fluid sampling in the unsaturated zone overlying the Post-Eocene aquifer system were made during the IGS studies but some indications of possible vertical recharge of direct precipitation have been derived by flow net analysis in the upper phreatic aquifer. Annual rainfall in the southern Sirte basin is very low (less than 3 mm at Tāzirbū) and flow net calculations demonstrate negligible recharge. In the Phase I area to the north, vertical recharge could be of the order of 2 to 3 mm annually which would approach 25% of the average annual precipitation recorded at nearby Jālū. Limited sampling for tritium has not confirmed the deduction. However all samples analysed were from shallow wells in the Jālū oasis area and showed negligible values, mainly less than one tritium unit. The sample sites selected had the disadvantage that significant moisture deficits are likely to be developed in the surface sands in oasis areas due to evapotranspiration from standing vegetation which could effectively inhibit recharge under the current climate. More unequivocal evidence would be provided by sampling wells with deeper water levels away from existing oasis areas. It may be noted that in the only exploration wells in the Phase 1 area which were screened at the water table, a few metres of fresher water overlies more mineralised water of the main aquifer and could possibly be the effect of current recharge or recharge during the Holocene.

Recharge via run-off from the Haruj and Tibesti mountain masses is also possible. No rainfall or run-off data for the high Haruj are available but the marked curvature of the piezometric contours in the adjacent Post-Eocene aquifer is attributed to probable recharge. The Tibesti mountains are more remote from the Sirte basin but drainage patterns extend over the Tibesti sarir to the basin margins and some recharge by current flash floods could occur. In recent times (8,000-4,000 years BP) run-off from the Tibesti has demonstrably reached 800 km into the central Sirte basin (Pachur, 1980). Such wide dispersion of flash floods is not unknown in the central Sahara and distances of 400 km have been recorded in historical records. Their occurrence in the Sirte basin would accord with the constancy of topographic control and persistent downwarping within the basin throughout its evolution.

The percentage rainfall which produces run-off and ultimately recharge from hard rock mountain areas into marginal alluvial aquifers can be considerable. Burdon (1972) estimated 33% of run-off and recharge from a mountain region in Oman and subsequent detailed observations in the same area (Sir Alexander Gibb and Partners in association with the Institute of Hydrology, 1976) of rainfall and wadi flows demonstrated groundwater recharge of the order of 23-29% of total rainfall. Although no data on wadi flows in the Tibesti region are available and rainfall records are available only for Zouar, some general estimates of possible run-off and recharge are worth making. Taking the area above 800 m elevation and assuming an average value of rainfall of 37 mm which is conservative, a 10-20% order of recharge would be equivalent to between 74 and 148 M m^3/a for the Kufra basin and 106-212 M m^3/a for the piedmont leading to the Sirte basin. The recharge estimates compare quite closely with the estimated outflow from the Kufra basin of between 70 and 160 M m^3/a. The aquifer could not be in equilibrium with this marginal recharge since otherwise in its phreatic condition, the age of the water at Kufra would be expected to be within the current climatic period (c. 5,000 years). Nonetheless an approach to equilibrium may exist. Since the rainfall of this region is extremely low it is assumed that any current recharge to the basin would be in marginal areas from surface run-off.

The situation in the Sirte basin is more complex. Small amounts of direct recharge by precipitation probably occurs in the basin north of latitude 28°00. Recharge via run-off could occur on the west and south-west margins of the basin as indicated by existing drainage networks and the curvature of the piezometric contours. To the south, recharge via lateral inflow from the Nubian is probable but with nil recharge from any source occurring in the south-east as shown by the trend of the piezometric contours. There is evidence that the present arid cycle has extended back for some 5,000 years. The great sand seas and extensive sarir plains were formed during this period. Some minor climatic fluctuations did however occur, of which at least one resulted in significant vegetational development in favourable locations. Plate I shows a soil pedestal dated at c. 1,000 years BP. Although major phreatic aquifers of this size could not be expected to have attained equilibrium during the current arid cycle, there are indications that for these low hydraulic gradients, the relatively small current recharge rates indicated may be such that conditions are now changing only very slowly and to a negligible extent.

The bulk of the water in the aquifers is fossil testifying to earlier recharge periods in the Pleistocene and Holocene. Several cycles dating back to at least 35,000 years can be recognised from the various groups of groundwater ages and in general show good correlation with palaeohydrological cycles determined by other methods.

<u>35,000-15,000 years BP.</u>

This interval forms part of a lengthy cold but humid period, well documented in the Mediterranean region (McBurney, 1968). It corresponds with the late Würm glacial period. Regional groundwater recharge appears to have occurred over the Kufra and Sirte basins during the early part from 35,000-25,000 years BP judging by observed groundwater ages from widely spaced sites. A widespread drainage network presumably existed but no contemporaneous lacustrine deposits have been identified. However high water levels in the central topographic depression (Figure 2) could account for the belt of brackish water in the PMM aquifer coincident with the depression to the south of Jālū (Figure 8) where lithological control appears inadequate to explain the high mineralisation. The explanation would attribute the phenomenon to the effects of evaporation in oasis or sabkhat areas with high water levels and making due allowance for subsequent northerly flow. A similar effect occurs to the north of the present oasis areas but involving water of more recent recharge (8,000-5,000 years BP).

Between 25,000 and 15,000 years BP, recharge appears to have been more localised in the region with dated groundwater known only in the northwest of the Sirte basin. The period is of declining humidity and the latter half is recognised in the Sahara as one of extreme aridity (Maley, 1977; Street and Grove, 1979). The groundwater occurrence of this age can most reasonably be assumed to have displaced older water with initial recharge from run-off in marginal piedmont areas. Permeability values, piezometric gradients and distances are consistent with run-off most probably occurring from the Haruj uplands. The contrast between the fresh groundwater lobe in the north-west of the Sirte basin and the somewhat higher mineralisation in the north-east of the basin on the opposite side of the topographic depression can reasonably be attributed to lack of flushing since no comparable highlands occur to the east.

The absence of flushing waters of intermediate age in the Kufra basin seems a little surprising and may indicate that in southern Libya during this period, aridity was even more extreme and precluded recharge via run-off. It should also be noted that following the same arguments, more mineralised waters may also be expected downgradient of the Kufra oasis. The length of this wedge would be accordance with previous water levels and flow velocities.

15,000-8,000 years BP.

Hyperarid climate with no groundwater recharge recorded.

8,000-5,000 years BP.

This represents a warm humid period recognised generally throughout North Africa with high lake levels and high Nile discharge. Residual major wadi trends which are in places overlain by dune sands of the current arid phase are apparent in the south and west of the Sirte basin stemming from the main highland areas. A fairly dense drainage network incised into surface caliche has been identified below the Calanscio sand sea (Di Cesare et al., 1963) and its absence in the adjacent sarir must indicate its later obliteration by deflation. More precise carbon and faunal dating (8,000-3,000 years BP) of wadi alluvium in the centre of the basin have been provided by Pachur (1980). The likelihood of flowing wadis of this period extending also across the northern Sirte basin is indicated by the elongated belts of fresher water, one of which has been dated and provided comparable ages. The conditions during this period appear to have permitted localised recharge below wadis but inhibited more regional recharge to the underlying aquifers. Pachur (1980) has described the probable environment as characterised by *'widespread shallow swamp-like places . . . light vegetation . . . cattle rearing . . . but also some morphological proof of wind influence'*, in effect semi-arid. Such conditions are likely to build up fairly high moisture deficits in surface sands which would preclude regional recharge even with annual rainfall exceeding 400 mm. Comparable conditions to those described exist at the present time in the Kalahari region and detailed studies (Foster, 1979) in the unsaturated Kalahari Sands indicate that a thickness of more than 4 m precludes deep recharge.

Additional clarification has been sought by the construction of a strip aquifer model along a 400 km longitudinal section between latitudes 26 and 30^{o}N through the Sirte basin and orthogonal to the piezometric contours (Figure 7). Transmissivities to the top of the main clay layer in the Lower and Middle Miocene are based on the results of aquifer test analyses and spaced as shown (Figure 10). Plots of piezometric sections including the observed and various modelled surfaces are also shown. For transient conditions a specific yield of 0.1 has been used.

A regional phreatic aquifer, such as occurs here, with relatively low transmissivity and high storativity (specific yield), and discharging across a narrow front will react very slowly to reductions in recharge. For significant changes, periods of the order of tens of thousands of years would be needed to re-establish a new equilibrium. For the same reasons, when recharge increases, the water table will rise relatively rapidly but equilibrium will be established soon after regional runoff commences. In contrast, artesian aquifers will react overall more quickly to any changes in recharge due to the low storativity (artesian) and relatively small area of phreatic outcrop (Issar et.al., 1972).

The first model runs (Figure 10a) assumed no lateral inflow at the southern margin of the basin. The initial water level was raised to ground level in the central topographic depression (Figure 1) by a uniform vertical input. A complete cessation of recharge is then postulated and recession piezometric surfaces obtained for various elapsed times between 2000 and 11000 years. Apart from some differences in level at the south end of the section, the comparison of observed and modelled results demonstrate that the observed level could represent a 'fossil' transient surface of 5000 years from an initial 'aquifer-full' condition corresponding in time with the termination of the last significant pluvial in the Holocene (8000-5000 years BP). Recession levels corresponding to the previous and more marked pluvial would show levels appreciably lower than at the present day. Although a transient surface of 5000 years is feasible, the absence of water of this general age (or of intermediate values consistent with mixing) in the main basin opposes the interpretation.

The second series of runs (Figure 10b) also assumed a complete cessation of vertical recharge to the aquifer but with a continuance of an appreciable lateral inflow from the Kufra basin. As noted in a previous section, hydrogeological evidence indicates the probable occurrence of inflow at the southern margin of the Sirte basin. The inflow rates assumed in the model correspond with the present gradient and transmissivity in the southern Sirte basin. They are somewhat less than the calculated outflow from the Kufra basin in the direction and are therefore realistic. Outflows at steady rates from the Kufra basin cannot be expected to occur over long periods of time under recession conditions but in a basin of this size, head changes must have occurred very slowly. The form of the modelled surfaces correspond rather more closely to the observed piezometric surface than do those in 10(a) but with some divergence in the north. Additionally the nearest recession levels (9000-20,000) to the observed level are closer in age to the measured ages in the main basin. Small adjustments to the rate of inflow could increase the convergence of observed and calculated recession ages.

The assumed recession with appropriate modifications to the lateral inflow from the south would obtain correspondence for the age of the groundwater in the Kufra basin and the centre of the Sirte basin but not for the younger ages (21,000 to 14,000 and 8000 to 5000 years) in the north of the basin. More localised recharge of younger waters must be postulated and in an earlier section it was suggested that flushing by recharge following runoff from the Haruj highlands to the west of the Sirte basin might have occurred. A similar effect could be obtained by small amounts of vertical recharge from precipitation sustained over long periods of time and localised in the north of the basin. It has been suggested earlier that small amounts of recharge (1.3 mm/a) could be occurring in the north at the present time. In Figure 10(c), a steady state modelled level is shown with nil recharge in the south, other than lateral inflow, and with 1.1 mm/a recharge in the north. The observed and modelled water levels correspond closely. Equilibrium would require some 30,000 years to be attained from an initial aquifer-full condition. Groundwater ages in the north of the basin would be mixed and intermediate values anticipated from pumped well determinations which could correspond with measured ages. Although the conditions over the lengthy period following the last late Pleistocene regional pluvial are known to have fluctuated, the general correlation has some credence given the known variations in the groundwater age dates and the general trend of climatic change. Additional groundwater age dates are needed to confirm the interpretation, particularly from different levels in vertical sections of the aquifer.

In summary, the model results have demonstrated a convergence of observed and modelled levels consistent with an age in the Kufra and the main Sirte basin corresponding to the latest Pleistocene pluvial with younger waters restricted to the north of the basin. Recharge during this lengthy recession would have varied and at certain times seems to have been augmented by runoff, notably in the period 8000-5000 years BP but the overall effects are consistent with small but sustained amounts of recharge occurring under arid to semi-arid conditions. This would be in addition to localised recharge via runoff from the Haruj and Tibesti mountains. The present water levels may well be fairly close to equilibrium despite the general aridity of the region.

ACKNOWLEDGEMENTS

The 1971-75 investigations were carried out in collaboration with the Kufra and Sarir Authority and IGS wishes to express its appreciation to Mr M Khattab, Director General of the Authority and Mr Alan Craig, Chief Engineer, and to acknowledge the participiation of the Authority's professional staff which included S Ahmed, S M Hasnain, M Makhyoun, M M Milad and F Zubairi. This paper is published by permission of the Director, Institute of Geological Sciences, NERC.

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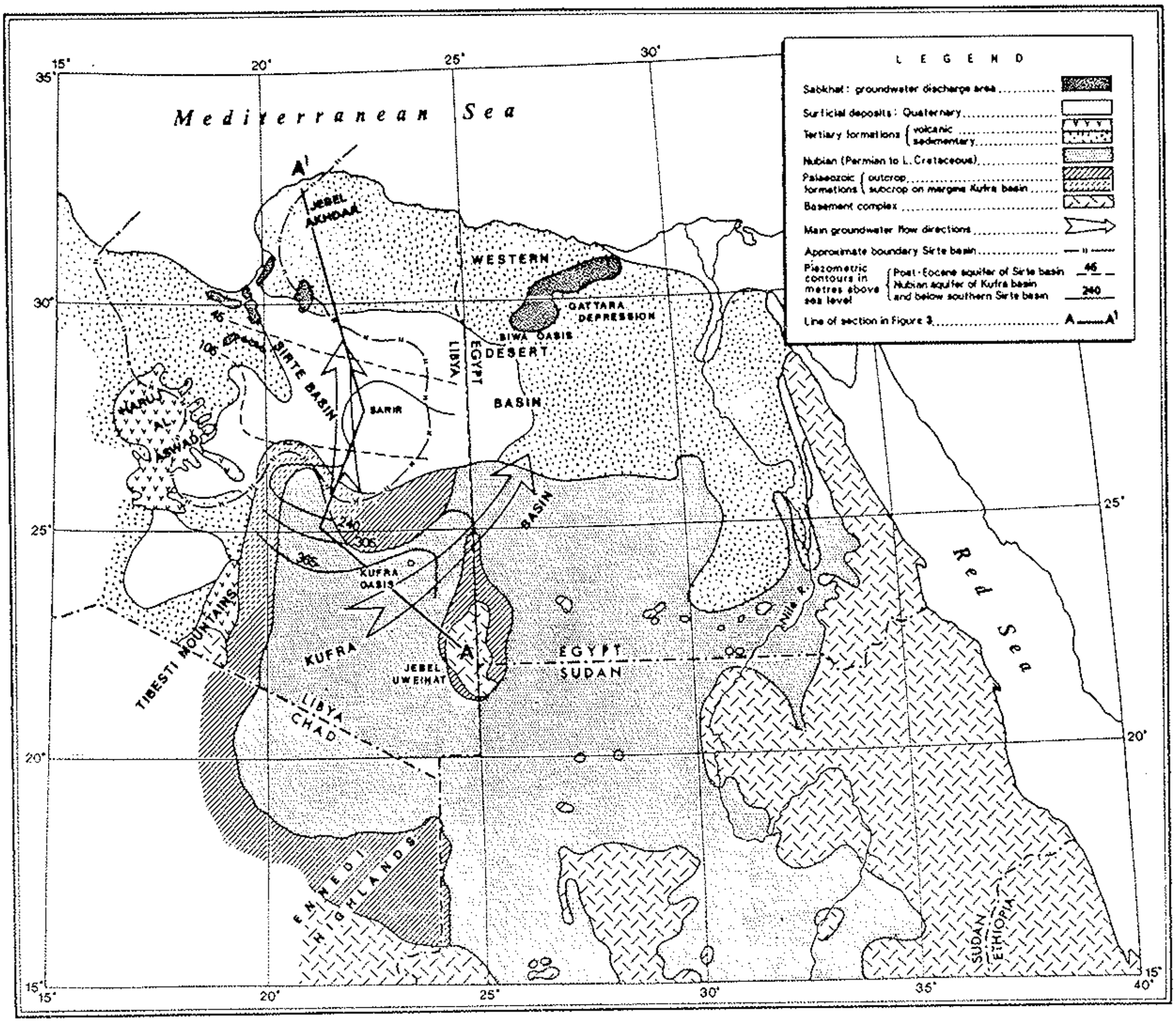
FIG. 1.



LEGEND
Sabkhat: groundwater discharge area
Surficial deposits: Quaternary
Tertiary formations { volcanic / sedimentary
Nubian (Permian to L. Cretaceous)
Palaeozoic formations { outcrop / subcrop on margins Kufra basin
Basement complex
Main groundwater flow directions
Approximate boundary Sirte basin
Piezometric contours in metres above sea level { Post-Eocene aquifer of Sirte basin 46 / Nubian aquifer of Kufra basin and below southern Sirte basin 240
Line of section in Figure 3 A — A1
Mediterranean Sea
Red Sea
JEBEL AKHDAR
SIRTE BASIN
HARUJ AL ASWAD
SARIR
WESTERN DESERT BASIN
QATTARA DEPRESSION
SIWA OASIS
LIBYA
EGYPT
SUDAN
CHAD
ETHIOPIA
KUFRA OASIS
KUFRA BASIN
JEBEL UWEINAT
TIBESTI MOUNTAINS
ENNEDI HIGHLANDS
Nile R.
A
A1
15°
20°
25°
30°
35°
40°

FIG. 2.

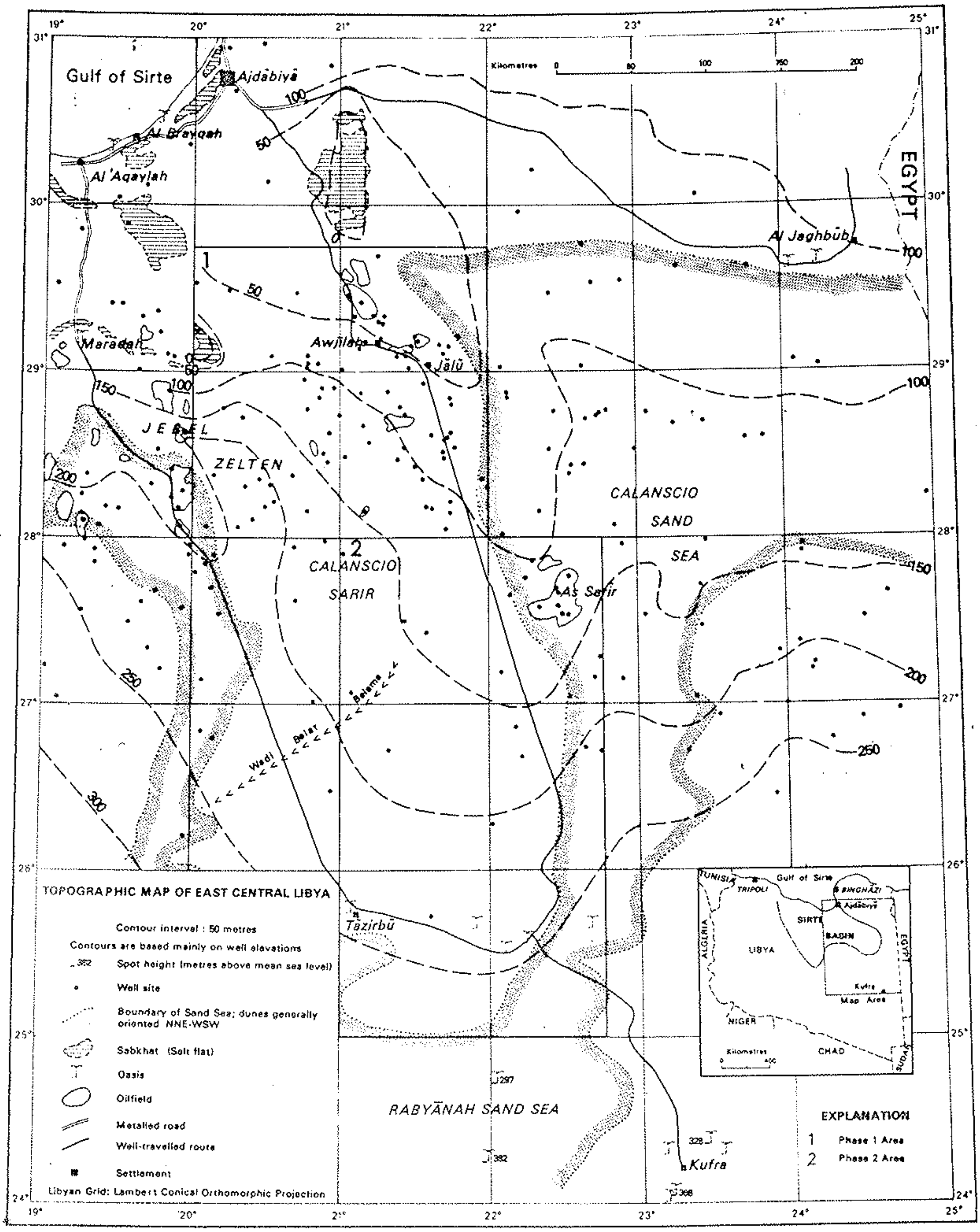

Gulf of Sirte
Ajdabiya
Al Brayqah
Al 'Aqaylah
EGYPT
Al Jaghbub
Maradah
Awjilah
Jalu
JEBEL
ZELTEN
CALANSCIO
SAND
SEA
CALANSCIO
SARIR
As Sarir
Wadi Belat
Beleme
Tazirbu
RABYANAH SAND SEA
Kufra
Kilometres
0
50
100
150
200
TOPOGRAPHIC MAP OF EAST CENTRAL LIBYA
Contour interval : 50 metres
Contours are based mainly on well elevations
Spot height (metres above mean sea level)
Well site
Boundary of Sand Sea; dunes generally oriented NNE-WSW
Sabkhat (Salt flat)
Oasis
Oilfield
Metalled road
Well-travelled route
Settlement
Libyan Grid: Lambert Conical Orthomorphic Projection
EXPLANATION
1 Phase 1 Area
2 Phase 2 Area
TUNISIA
TRIPOLI
Gulf of Sirte
BINGHAZI
Ajdabiya
SIRTE
BASIN
LIBYA
ALGERIA
EGYPT
Kufra
Map Area
NIGER
CHAD
SUDAN
Kilometres
19°
20°
21°
22°
23°
24°
25°
31°
30°
29°
28°
27°
26°
25°
24°

FIG.

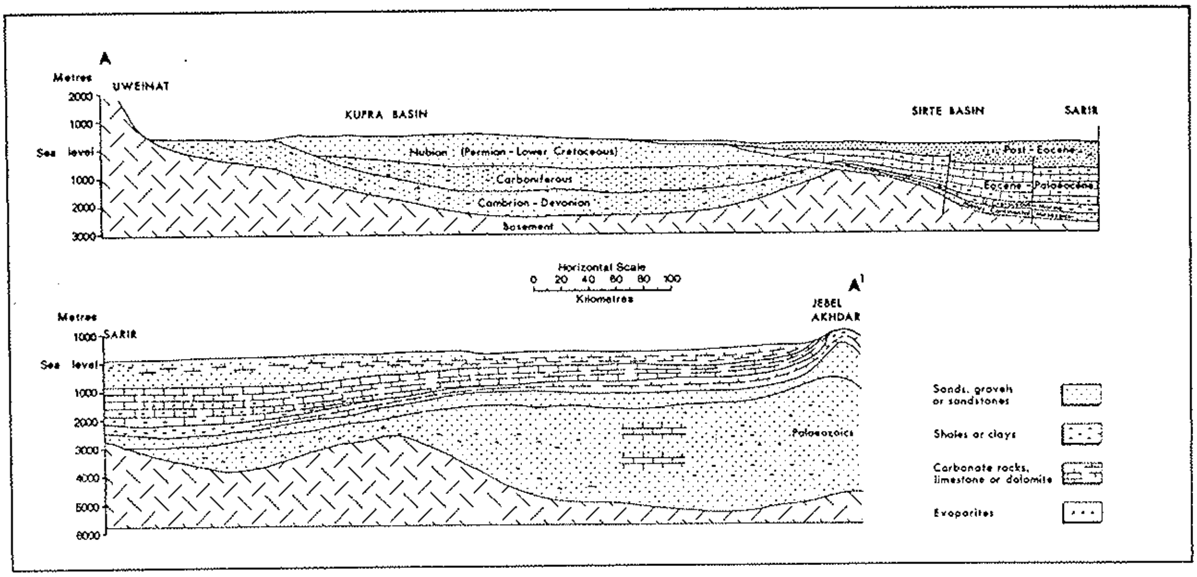

A
Metres
UWEINAT
2000
1000
Sea level
1000
2000
3000
KUFRA BASIN
Nubian (Permian - Lower Cretaceous)
Carboniferous
Cambrian - Devonian
Basement
SIRTE BASIN
SARIR
Post - Eocene
Eocene - Palaeocene
Horizontal Scale
0 20 40 60 80 100
Kilometres
A1
JEBEL
AKHDAR
Metres
1000
SARIR
Sea level
1000
2000
3000
4000
5000
6000
Palaeozoics
Sands, gravels or sandstones
Shales or clays
Carbonate rocks, limestone or dolomite
Evaporites

FIG. 4.

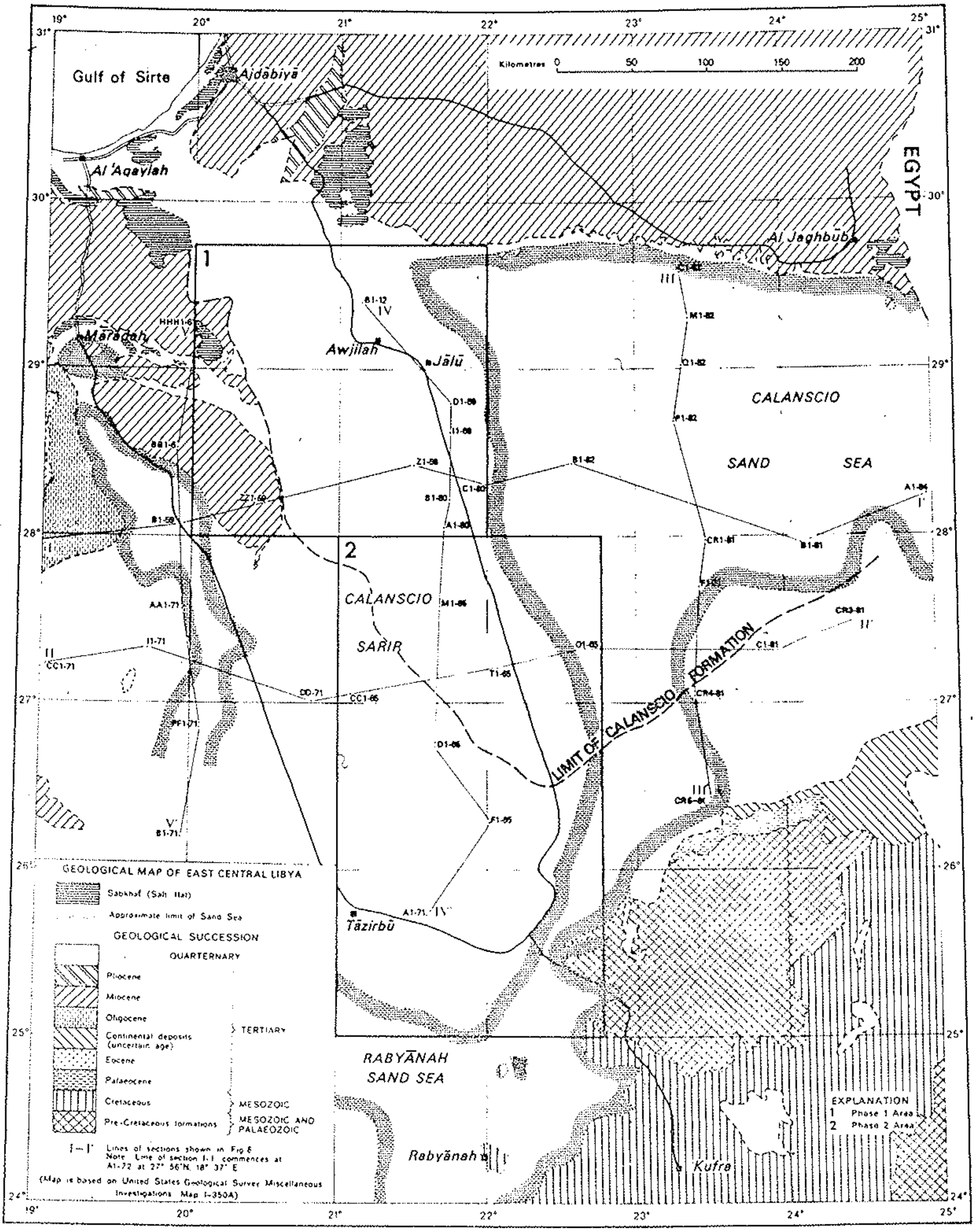
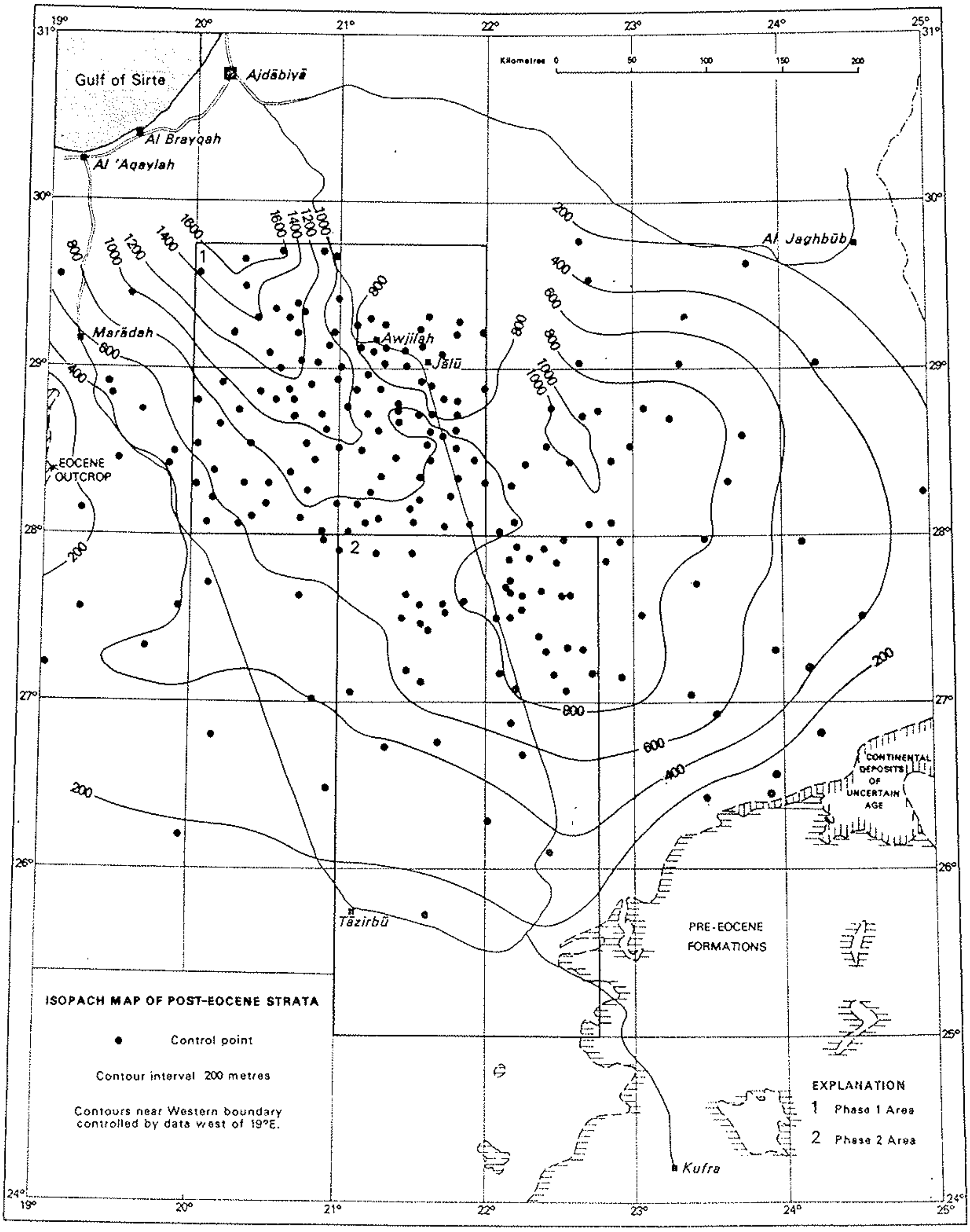
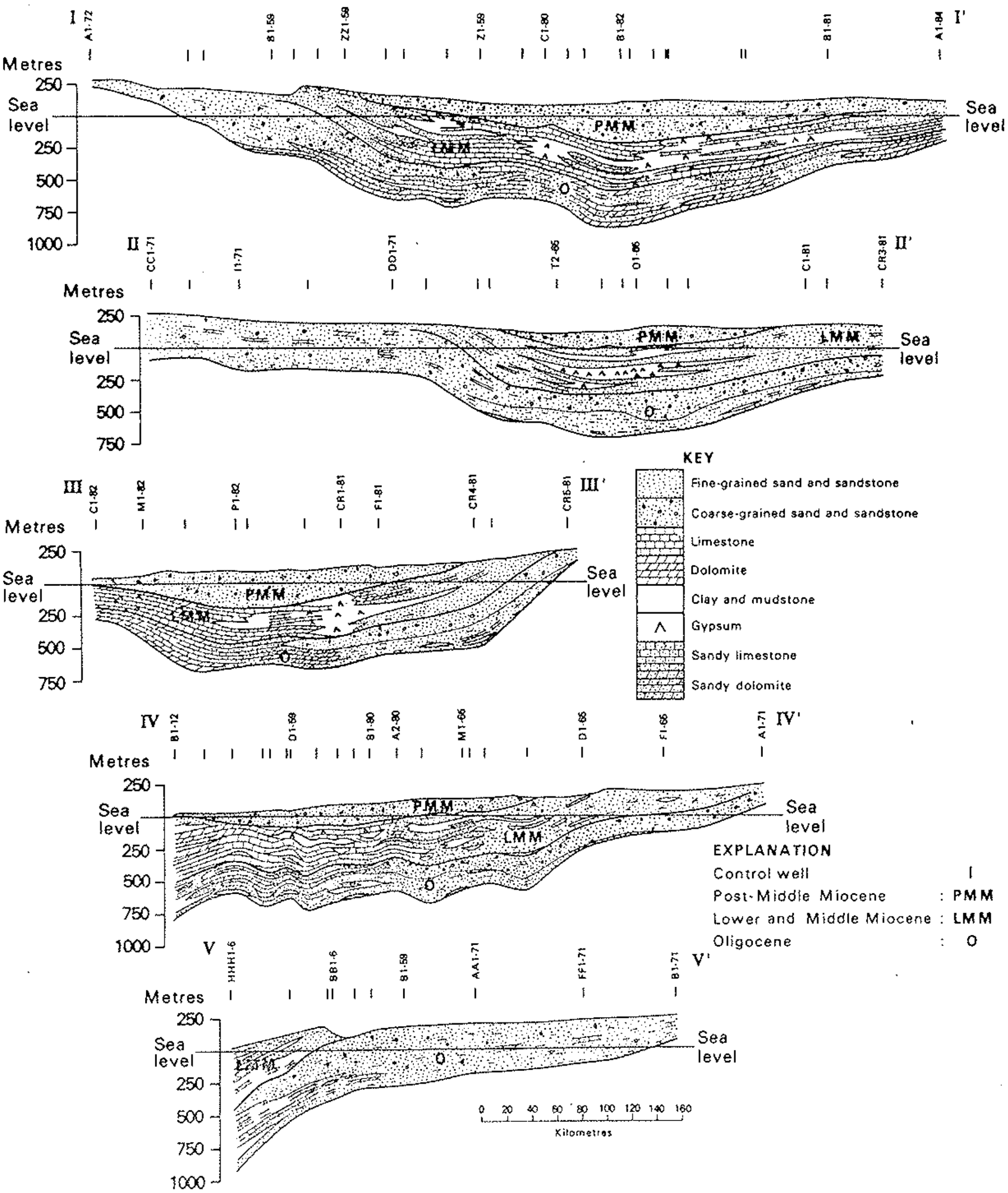

Gulf of Sirte
Ajdabiya
Al 'Aqaylah
EGYPT
Al Jaghbub
Marādah
Awjilah
Jālū
CALANSCIO
SAND SEA
CALANSCIO
SARIR
LIMIT OF CALANSCIO FORMATION
RABYĀNAH
SAND SEA
Rabyānah
Tāzirbū
Kufra
Kilometres 0 50 100 150 200
EXPLANATION
1 Phase 1 Area
2 Phase 2 Area
GEOLOGICAL MAP OF EAST CENTRAL LIBYA
Sabkhat (Salt flat)
Approximate limit of Sand Sea
GEOLOGICAL SUCCESSION
QUARTERNARY
Pliocene
Miocene
Oligocene
Continental deposits (uncertain age)
Eocene
Palaeocene
TERTIARY
Cretaceous
MESOZOIC
Pre-Cretaceous formations
MESOZOIC AND PALAEOZOIC
I — I' Lines of sections shown in Fig 6
Note Line of section I-I commences at A1-72 at 27° 56'N. 18° 37' E
(Map is based on United States Geological Survey Miscellaneous Investigations Map I-350A)

FIG.

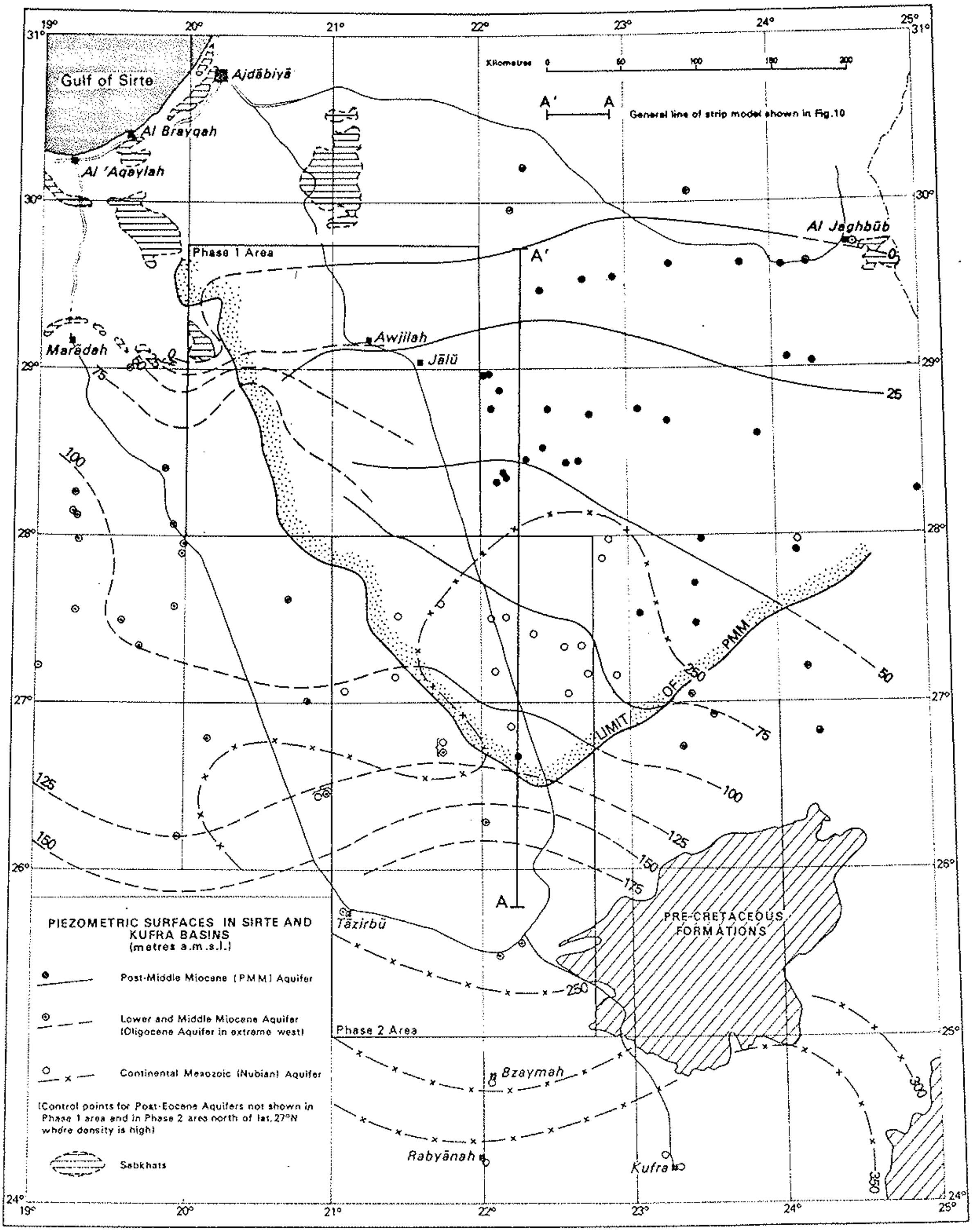

ISOPACH MAP OF POST-EOCENE STRATA
Control point
Contour interval 200 metres
Contours near Western boundary controlled by data west of 19°E.
EXPLANATION
1 Phase 1 Area
2 Phase 2 Area
Kilometres 0 50 100 150 200
Gulf of Sirte
Ajdābiyā
Al Brayqah
Al 'Aqaylah
Marādah
Awjilah
Jālū
Al Jaghbūb
Tāzirbū
Kufra
EOCENE OUTCROP
CONTINENTAL DEPOSITS OF UNCERTAIN AGE
PRE-EOCENE FORMATIONS
19° 20° 21° 22° 23° 24° 25°
31° 30° 29° 28° 27° 26° 25° 24°

FIG



I
I'
II
II'
III
III'
IV
IV'
V
V'
Metres
250
Sea level
500
750
1000
PMM
LMM
O
KEY
Fine-grained sand and sandstone
Coarse-grained sand and sandstone
Limestone
Dolomite
Clay and mudstone
Gypsum
Sandy limestone
Sandy dolomite
EXPLANATION
Control well
Post-Middle Miocene : PMM
Lower and Middle Miocene : LMM
Oligocene : O
0 20 40 60 80 100 120 140 160
Kilometres

FIG. 7.



Gulf of Sirte
Ajdābiyā
Al Brayqah
Al 'Aqaylah
Kilometres 0 50 100 150 200
A' A General line of strip model shown in Fig.10
Al Jaghbūb
Phase 1 Area
Awjilah
Jālū
Marādah
LIMIT OF PMM
PRE-CRETACEOUS FORMATIONS
Tāzirbū
Phase 2 Area
Bzaymah
Rabyānah
Kufra
PIEZOMETRIC SURFACES IN SIRTE AND KUFRA BASINS
(metres a.m.s.l.)
Post-Middle Miocene (PMM) Aquifer
Lower and Middle Miocene Aquifer (Oligocene Aquifer in extreme west)
Continental Mesozoic (Nubian) Aquifer
(Control points for Post-Eocene Aquifers not shown in Phase 1 area and in Phase 2 area north of lat. 27°N where density is high)
Sabkhats

FIG 8.

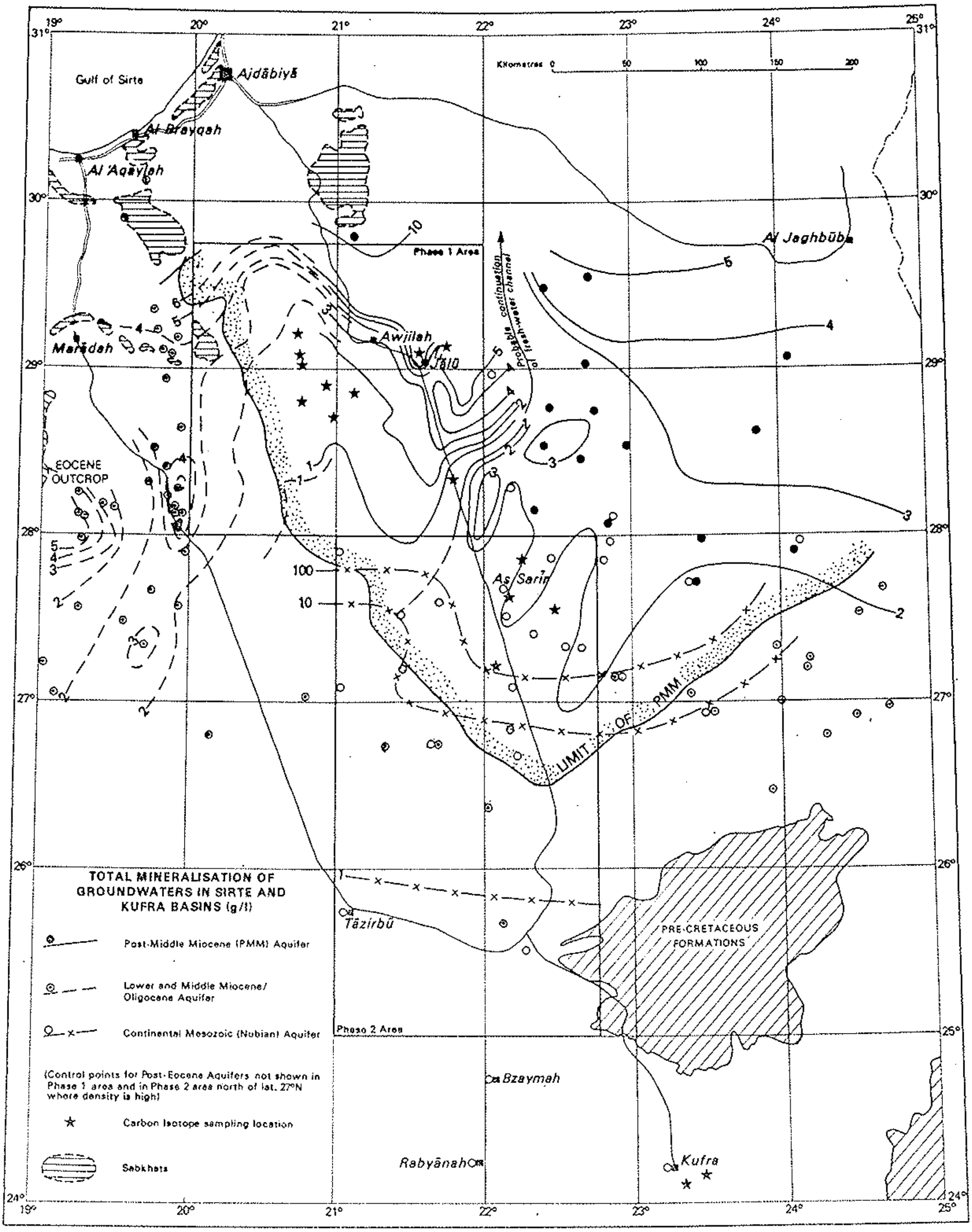
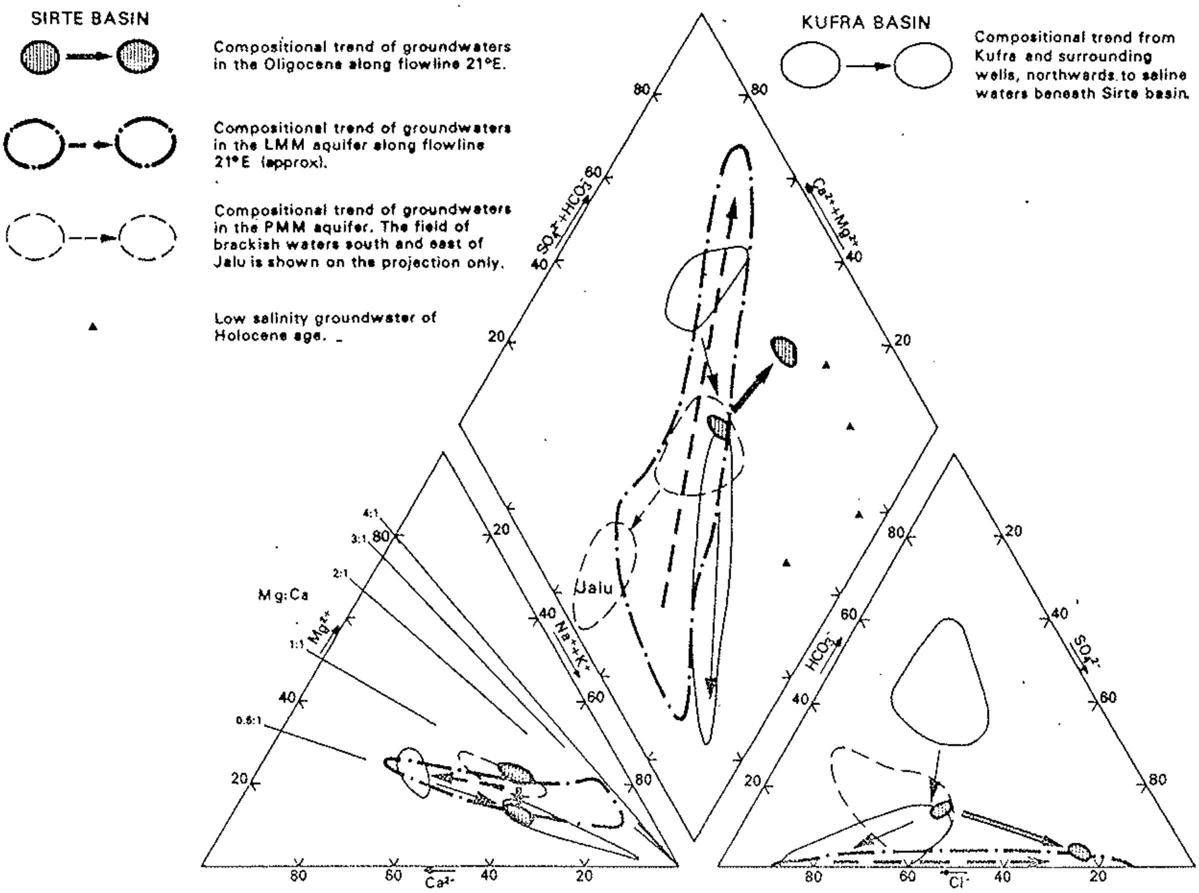
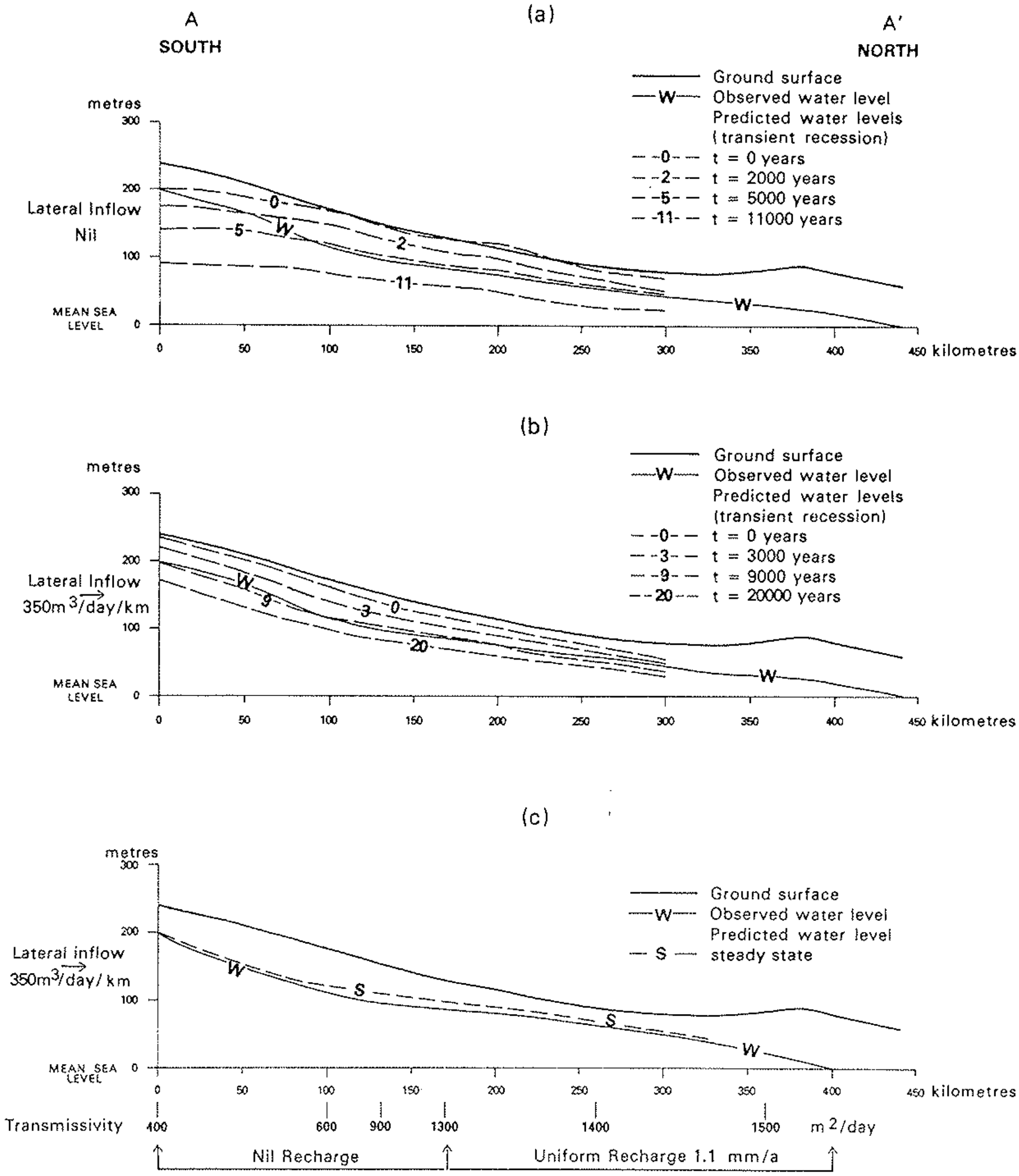

Gulf of Sirte
Ajdābiyā
Al Brayqah
Al 'Aqaylah
Marādah
Awjilah
Jalū
Al Jaghbūb
Kilometres 0 50 100 150 200
Phase 1 Area
Probable continuation of fresh-water channel
EOCENE OUTCROP
As Sarīr
LIMIT OF PMM
PRE-CRETACEOUS FORMATIONS
Tāzirbū
Phase 2 Area
Bzaymah
Rabyānah
Kufra
TOTAL MINERALISATION OF GROUNDWATERS IN SIRTE AND KUFRA BASINS (g/l)
Post-Middle Miocene (PMM) Aquifer
Lower and Middle Miocene/ Oligocene Aquifer
Continental Mesozoic (Nubian) Aquifer
(Control points for Post-Eocene Aquifers not shown in Phase 1 area and in Phase 2 area north of lat. 27°N where density is high)
Carbon Isotope sampling location
Sabkhats

FIG. 9.



SIRTE BASIN
Compositional trend of groundwaters in the Oligocene along flowline 21°E.
Compositional trend of groundwaters in the LMM aquifer along flowline 21°E (approx).
Compositional trend of groundwaters in the PMM aquifer. The field of brackish waters south and east of Jalu is shown on the projection only.
Low salinity groundwater of Holocene age.
KUFRA BASIN
Compositional trend from Kufra and surrounding wells, northwards to saline waters beneath Sirte basin.
Jalu
Mg:Ca
4:1
3:1
2:1
1:1
0.5:1
Mg2+
Ca2+
Na+ + K+
SO42- + HCO3-
Ca2+ + Mg2+
HCO3-
SO42-
Cl-
20
40
60
80

FIG. 10


(a)
A
SOUTH
A'
NORTH
Ground surface
W Observed water level
Predicted water levels (transient recession)
0 t = 0 years
2 t = 2000 years
5 t = 5000 years
11 t = 11000 years
metres
Lateral Inflow Nil
MEAN SEA LEVEL
kilometres
(b)
Ground surface
W Observed water level
Predicted water levels (transient recession)
0 t = 0 years
3 t = 3000 years
9 t = 9000 years
20 t = 20000 years
metres
Lateral Inflow 350m3/day/km
MEAN SEA LEVEL
kilometres
(c)
Ground surface
W Observed water level
Predicted water level
S steady state
metres
Lateral inflow 350m3/day/km
MEAN SEA LEVEL
kilometres
Transmissivity 400 600 900 1300 1400 1500 m2/day
Nil Recharge
Uniform Recharge 1.1 mm/a