

SOME PHYSICAL AND CHEMICAL PROPERTIES OF THE
SEDIMENTS FROM THE SOUTHWEST COASTAL PLAIN OF BAHRAIN

by

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JANUARY 1981

A thesis submitted for the degree of Master of
Philosophy of the University of London and for
the Diploma of Imperial College.

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ACKNOWLEDGEMENTS

In the name of ALLAH, the beneficent, the merciful, praise be to ALLAH.

This work would not have been possible without the help of many individuals. The author would like to acknowledge the help of:

His Excellency Mohamed Mahdi al-Tajir for generously sponsoring me throughout this study. I remain indebted to him, as without this grant it would have been impossible for me to undertake my studies at Imperial College.

The Government of Bahrain for permitting the use of the material for scientific research,

The directors of the "Bahrain Surface Materials Resources Survey": Drs. D. Brunsdon, J. C. Doornkamp and D. K. C. Jones.

Dr. P. R. Bush, my supervisor, for his help and advice, continuous encouragement, fruitful discussions and in particular for never being too busy to discuss any problem.

Dr. G. Evans for reading and discussing parts of the thesis.

Professor D. Shearman, Dr. H. F. Shaw and Miss M. Pugh for discussions and encouragement.

My research colleagues at Imperial College: Drs. H. Hassouba, A. Saleh, N. Sherif, F. Fatona, N. Gorur, A. Ibe and Messrs. D. O. L. Aikhionbare and F. Emre.

Drs. J. Ferguson, I. Megahid and Mr. Y. A. El Saie for providing and developing computer programmes.

Dr. H. Moneib for drafting the figures.

Messrs. R. Curtis, M. Gill, Mrs. G. Cumpsty, Miss L. Formoso and Dr. N. Walsh for technical assistance.

Miss Khadidjah Saleh for efficiently typing this document and Miss A. Napier for the tedious task of typing the tables.

To my parents to whom I shall remain for ever indebted and grateful for their moral support, encouragement and guidance throughout their lives.

Finally, I would like to dedicate this work to my wife, Hoda, for her tremendous support, understanding and help in many ways, and to my son, Hatem, and my daughter, Shahinda.

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ABSTRACT

On the southwest coast of Bahrain island is a low Quaternary coastal plain complex, which was formed as a result of a series of events initiated by the drowning of the low coastal desert dunes of Arabia and the formation of the gulfs of Bahrain and Salwa during the Flandrian transgression. The desert sands drowned by the transgression were reworked by the sea and mixed with newly formed marine carbonates. Deposition of this mixed sediment on the coast of Bahrain followed by modification by wind, wind-generated waves and occasional storms has produced the coastal plain in its present complex form. The aridity of the region has resulted in the formation of very concentrated groundwaters which has led to the early diagenetic formation of gypsum and anhydrite. Halite, potassium and magnesium salts are not preserved because of the high humidity.

Six geomorphic units have been identified, these are; beach ridges, sabkha, salt pan, accretion zone, platform and aeolian sands with dune form.

The sediments are mainly composed of quartz with lesser amounts of calcite, aragonite, gypsum and anhydrite. Gypsum and anhydrite sometimes dominate in the sediments of the salt pan but they rarely form extensive deposits, and carbonates are sometimes dominant in the sediments of the beach ridges, accretion zone and platform.

Due to the abundance of quartz and the absence of fine grained carbonates reaction between the interstitial waters and the host sediments are minimal and the formation of diagenetic minerals has mainly been by precipitation from concentrated interstitial waters. These interstitial waters are complex in origin, and appear to have originated by the mixing of sea water derived from the adjacent Gulf, with groundwater derived from the adjoining bedrock and with surface water either by direct

precipitation and/or runoff.

This coastal complex demonstrates that in this type of environment numerous facies may exist in very close proximity, so that in the geologic record rapid local lithological variations may be expected both vertically and laterally.

The material used for the research will be placed in boxes, labelled and stored in the Geology Department store room,

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CHAPTER ONE

Introduction, the Arabian Gulf, Bahrain
and the methods of study.

1.1 The aim of the study:

Detailed investigations have been carried out on the subtidal to supratidal carbonate and evaporite sediments forming in coastal plains characterised by low clastic input and high net evaporation. In the Arabian Gulf (commonly known in the literature as the Persian Gulf) investigations of modern environments have been concentrated on the coastal plains of the United Arab Emirates (Papers in Purser, 1973; Curtis et al, 1963; Evans, 1966; Evans and Shearman, 1964; Evans and Bush, 1969; Evans et al, 1964; 1969; Kinsman, 1964; 1966; 1969; 1971; Shearman, 1963; 1966; 1978; Butler, 1965; 1969; 1970; Bush, 1973; Evamy, 1973; Kendall and Skipwith, 1968; 1969 a; 1969 b; Park, 1973; Patterson and Kinsman, 1977; Hsu and Schneider, 1973; Schneider, 1974; McKenzie and Hsu, 1974) and Qatar (Houbolt, 1957; Taylor and Illing, 1969; Shinn, 1973; Illing et al, 1965). Less intensive investigations have been carried out on the coastal plains of Saudi Arabia, Kuwait and Bahrain, where carbonate sediments grade into siliciclastic sediments and coastal sabkhas are formed with quartz sand sediments (Johnson et al, 1978; B.S.M.R.S., 1976; Brunsden et al, 1980; Saleh, 1979).

The purpose of this study is to investigate in detail the physical and chemical properties of the sediments of the coastal plain complex on the southwest of Bahrain, in order to improve the understanding of the origin and geological evolution of that area. The wider aims are to broaden the knowledge of the processes and products of sedimentation of coastal sabkhas produced in quartz-sand sediments, and to compare those of Bahrain with other arid coastal plain areas.

The material for this study was collected by members of "The Bahrain Surface Materials Resources Survey", hereafter referred to as "B.S.M.R.S.". The fieldwork was carried out in two periods; in December, 1974 and in April, 1975.

For a better understanding of the area of study, a brief account of the geology of the Arabian Gulf and Bahrain will follow.

1.2 The Arabian Gulf:

The present day Gulf is a shallow epicontinental marginal sea (Fig.1.1), its basin being a tectonic depression of late Pliocene to Pleistocene age (Kassler, 1973). The Gulf lies between latitudes 24° -

30° 30'N, and between longitudes 48° - 56° 30'E. Its length is ca. 1,000Km., while its width is between 200 - 300Km., and it occupies an area of approximately 226,000Km.². Its average depth is ca. 35 metres and its maximum depth is ca. 100 metres near its 60Km. wide entrance at the Straits of Hormuz (Fig.1.1).

1.2.1 Bathymetry of the Arabian Gulf:

The entire basin of the Gulf lies upon the continental shelf, whose margin and slope occur in the Gulf of Oman. The basin is asymmetrical about its axis and has a northwest trend which lies relatively close to the Iranian side (Fig.1.1). The sea floor slopes down from the Iranian side of the basin (1.75m/Km) but more gently on the Arabian side (0.35m/Km). The position and orientation of the axis are a result of the interference and superimposition of two contrasting tectonic styles; the Iranian fold belt to the north, formed during the Plio-Pleistocene Zagros orogeny, and the stable Precambrian shield of Arabia (the Precambrian Arabian shield is tilted and overlaid by Phanerozoic sediments) to the south and west characterised by large, low dipping anticlines, with N-S or NE-SW Arabian trends. These Arabian folds probably had a continuous movement since the Mesozoic as a result of salt growth (Kassler, 1973).

The Gulf has been subdivided into a series of bathymetric provinces by Seibold and Vollbrecht, 1969 (Fig.1.1); the Arabian side, known as the Arabian Shallow Shelf or Arabian Homocline, was further subdivided into the Hasa Terrace and the Pearl Bank Ridge, NW and SE of Qatar respectively. This homocline has a very gently slope, but permits a high degree of wave agitation along the Arabian coast thus affecting its morphology and sedimentology. The Iranian side has a well-defined ridge termed the Central Swell which subdivides it into two secondary depressions; the Western and Central Basins (Fig.1.1).

These basins and shelves are locally further modified by complicated systems of highs and depressions which result in complex local sediment patterns (Purser and Seibold, 1973).

1.2.2 Regional late Pleistocene and Holocene sedimentation:

Stoffers and Ross (1979) from cores collected from the Arabian Gulf and the Gulf of Oman, identified three distinct lithologic units which could be correlated over most of the Gulf, these are:

Unit 1: The uppermost unit which is an olive grey marl of variable

thickness, (0.5 to 1m) which was deposited within the last 5,000 - 6,000 years B.P. The sediments are very silty clays and contain abundant biogenic constituents. The carbonate content is approximately 55% with high-magnesium calcite as the main carbonate mineral present.

Unit 2: The middle unit is a light greenish-grey carbonate mud, with occasional intercalated lithified carbonate layers, of variable thickness (0.1 to 1.0m) which was deposited between 6,000 - 12,000 years B.P. The sediments are mainly composed of clay-sized aragonite needles, while the coarser fractions contain abundant oolites and pellets. The carbonate content is more than 70% with aragonite as the main carbonate mineral present.

Unit 3: The bottom unit is a greyish brown detrital silt, the sediments being highly compact in the lower parts of the unit. It was deposited between 12,000 - 30,000 years B.P. The carbonate content is 35 - 59% with calcite, dolomite and calcian-dolomite as the main carbonate minerals present,

Dust samples collected by suction techniques from dominant NW winds were composed of illite, chlorite, palygorskite, quartz, calcite and dolomite. The carbonate content varies from 15 - 34%.

1.2.3. Regional geomorphic and structural evolution:

The effects of climatic, tectonic, sedimentologic and sea level changes have had a profound influence on the evolution of the area and on its geomorphology. This was illustrated by P. Kassler, 1973, who studied the origin of the present day morphology of the Arabian Gulf (for summary see Fig.1.2).

The Gulf is a tectonic basin of late Pliocene to Pleistocene age, whose morphology is greatly influenced by the tectonic style. The pre-Pliocene movements were mainly growth structures; linear and domal growth structures and piercement domes. Their origin may be due to salt diapirism, but the linear growth structures may have been due to basement uplift. The growth structures are characterised by prolonged upward movement during sedimentation and low vertical relief. The effects of these growth structures have, except locally, been obscured by later tectonics and by sedimentation. Bahrain and Qatar surface structures owe their present form largely to the pre-Pliocene movements.

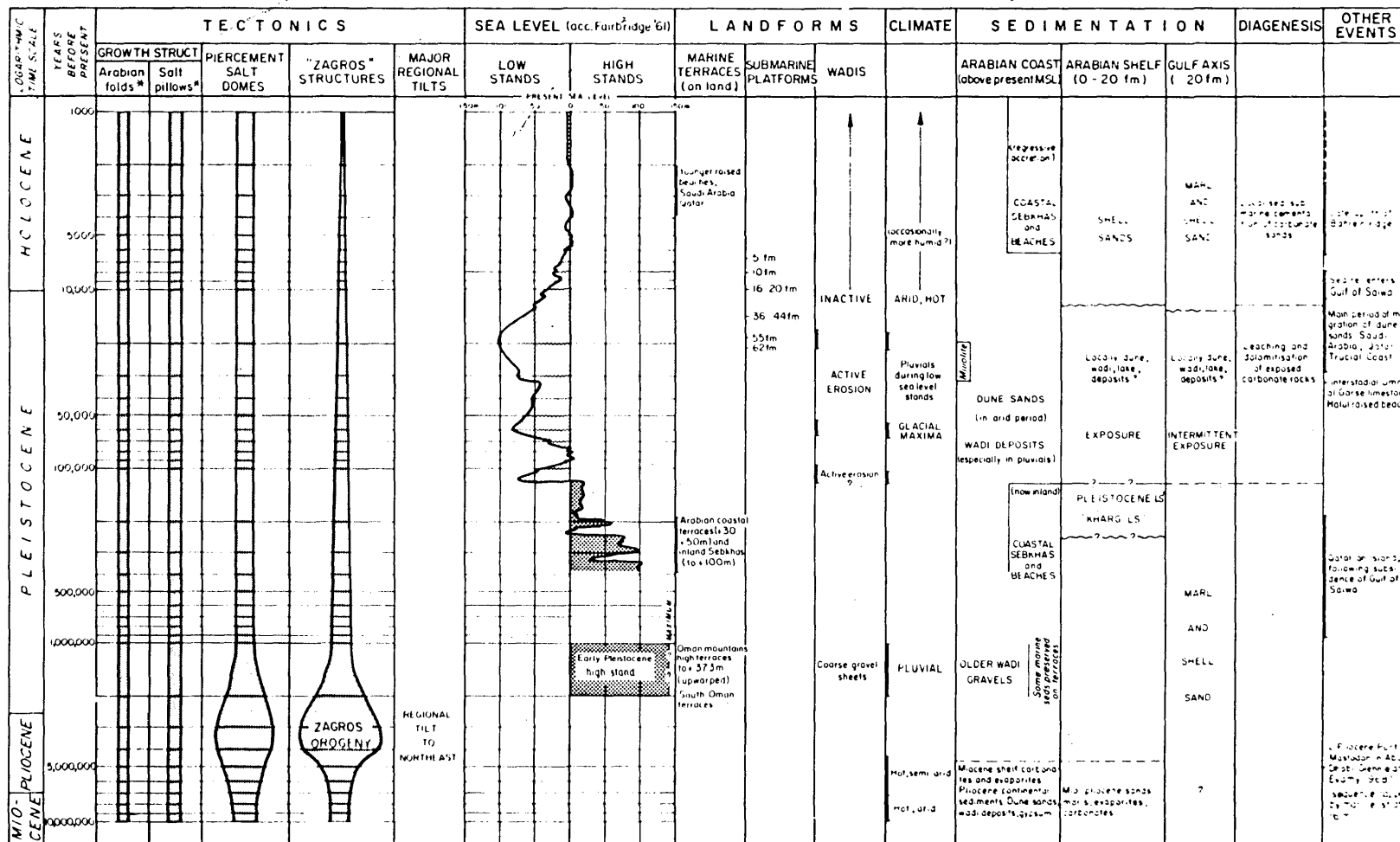


Fig. 1.2 A summary of the main tectonic, sea level, geomorphic, climatic and sedimentologic controls affecting the evolution of landforms in the Arabian Gulf (after Kassler, 1973).

The Plio-Pleistocene period was one of extensive tectonic activity and of sea level fluctuations which controlled the morphologic framework of the Arabian Gulf. In Iran, the tectonic control was by the intense Zagros fold movements, which were extensive on the Iranian mainland, diminishing seawards towards the Iranian coast. The axial trend of the Gulf is a Zagros feature and consists of two synclines (previously referred to as the Western and Central basins) separated by the Central Swell which is probably a large Zagros anticline (Kassler, 1973). On the Iranian mainland, salt dome extrusion was due in part to Zagros fold movements. In Arabia, the Salwa-Bahrain-Qatar structural complex of N-S Arabian trend was deformed slightly by Zagros, NW - SE trend, folds. During the Zagros movements, the Gulf axis subsided and the Arabian Homocline tilted seawards in a northeasterly direction. This is also shown by a NE trend of Quaternary wadigravels indicating stream drainage flowing from central Saudi Arabia across southern Qatar and Abu Dhabi (Powers et al, 1966). Extensive extrusion of salt domes occurred, some of which may have occurred at intersections of Zagros folds and Arabian growth structures. Accompanying the folds were NW to N-NW faults and fractures which may have controlled the Hasa and U.A.E. coasts. Little precise dating of the Oman Mountains uplift is known, but a zone of tectonic and topographic complexity occupying the whole of the Hormuz Strait suggests a close connection with the Zagros movements (Kassler, 1973). Plio-Pleistocene sedimentation partly subdued the morphology of the Gulf.

The effects of the Quaternary movements on the morphology has mainly been the local adjustment of existing features by subaerial and coastal erosion. On the Iranian side, the Zagros orogeny has continued into the Recent, with uplift of the mountain belt and with complementary depression of the Gulf (Lees and Falcon, 1952). On several coastal islands sub-Recent raised beaches have been formed indicating further movement. On the Arabian side, the Oman Mountains were uplifted considerably as shown by a series of raised marine terraces at elevations up to +373m. on the eastern flank of the range (Lees, 1928). These terraces may have been formed during the period of higher sea level during the Pleistocene (ca. +150m.). The shapes of shoals and depressions east of Qatar on the Arabian Homocline reflect interference between Zagros and Arabian trends. The shoals have a slightly more Zagros trend indicating a slight re-orientation of old structures by subsequent movements. The Gulf of Salwa subsided, and Qatar became an

island, but relatively small vertical movements have led to the rising of Bahrain in the last few thousand years. Piercement salt dome islands attain topographic elevations well above those of nearby coastal areas, and are the most spectacular Quaternary movements in the area. A combination of erosion of highs and sedimentation in depressions has led to a reduction in the relief.

Regional climatic changes and sea level fluctuations played an important role in the geomorphic evolution. During the Pliocene, the climate was hot and semi-arid, but towards its end and in early Pleistocene time when the sea level was high, the climate was characterised by pluvials. During this time much water flowed in the wadis and coarse sheets of alluvial gravel were deposited (previously described Quaternary wadi gravels) just to the south of Bahrain (Kassler, 1973; Al-Sayari and Zotl, 1978).

During the Pleistocene glaciations, the sea level was lower than it is at present. This is shown by the existence of both submarine platforms and drowned and buried river valleys. Several submarine platforms were recognised and described by Houbolt, 1957, who regarded them as indicating stages in the post-glacial rise of sea level. He considers they were formed in pairs, each temporary sea level being marked by a surface of accumulation and by a surface of abrasion. It is questionable, however, whether these conditions are comparable with those in late Pleistocene and early Holocene times, when the sea level was rising rapidly (Curry, 1961; Fairbridge, 1961). In the circumstances, erosion seems likely to have been the dominant process of platform formation. The platforms are therefore regarded as surfaces cut by the sea during pauses in the post-glacial rise in sea level, at levels corresponding to mean low-tide level at the time (Fairbridge, 1961, p.140). Thus the step from one platform to the next level is a fossil coastline.

Six main platforms are defined, mainly from studies of the Arabian parts of the Gulf.

These platforms are erosional (Fig. 1.3) and are:

-9m. -18m. -29/-37m. -66/-80m. -110m.
 -120m.

At the moment there is no direct evidence of the age of these platforms

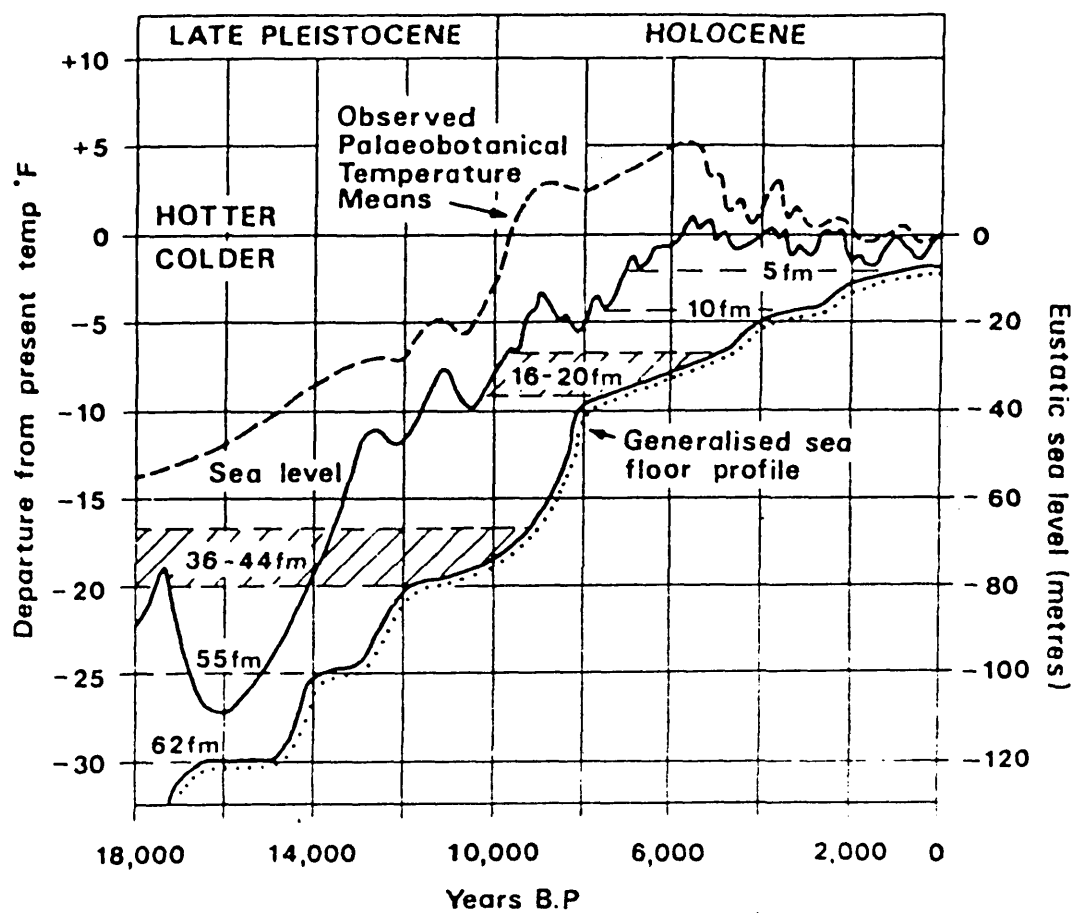


Fig. 1.3 Late Pleistocene and Holocene temperature and sea level changes, and submarine platforms in the Arabian Gulf (after Kassler, 1973).

however an attempt based on altimetric correlation with Fairbridge's curve has been used as a working hypothesis (Fig.1.3). The broad agreement of the Arabian Gulf levels with those of Curray, 1961, and Fairbridge, 1961, as well as the constancy of individual terrace elevations within the Gulf, suggests that the Gulf is tectonically stable today (Kassler, 1973).

The deepest platform of -120m. (this level occurs only in the Gulf of Oman and the Hormuz Straits) shows that during the Wurm glaciation, 70,000 - 17,000 years B.P. according to Fairbridge, op. cit., continental conditions prevailed over almost the whole of the Gulf, the sea having withdrawn to the Hormuz Strait. During maximum regression, the basin was a very large valley carrying Tigris-Euphrates waters directly into the Gulf of Oman (Kassler, 1973). Under these conditions, greyish brown terrigenous sediments were deposited in the Gulf, and aeolian transport and deposits were important (Stoffers and Ross, 1979).

A partial return of the sea occurred about 30,000 years B.P. (During this time the sea level was -40m. according to Fairbridge, 1961, or -15m. according to Curray, 1961).

The post-glacial sea level rise began about 17,000 years B.P. and it reached its present level some 5,000 years ago, in a series of rapid advances separated by still-stands or short regressions (Evans, 1979). This rise is known as the Flandrian Transgression (Curray, 1961; Fairbridge, 1961). The aragonite sedimentation which was taking place at that period evolved into the marl sedimentation which is occurring today; around 5,000 years B.P. (Stoffers and Ross, 1979), sedimentation being concentrated in topographic depressions tending to result in the smoothing out of the relief.

To summarise, the morphologic framework of the Gulf was formed in the Plio-Pleistocene tectonic phase, and Quaternary tectonics, sea level fluctuations and sedimentation have modified the morphology locally.

1.3 Previous Work:

Most of the published work on the surface geology of Bahrain was at a reconnaissance level.

Pilgrim, 1908, gave an account of the surface geology of Bahrain,

in which he outlined the distribution of the rock units and their relationships to topography. He established the Eocene age of the rocks using palaeontological evidence.

Willis, 1967, gave an account of a stratigraphic succession based on data from shallow boreholes and surface observations (Table 1.1.c). No palaeontological evidence was presented by Willis to substantiate the ages of the units described, but ages were based on correlation of the units of Bahrain with corresponding units in Saudi Arabia which have a comparable sequence and structure. The units in Saudi Arabia have been dated palaeontologically by Powers et al, 1966, (Table 1.1.b). He also produced a geological map of Bahrain.

Wright, 1967, and Wright and Ayub, 1975, discussed the geology and groundwater resources of Bahrain.

The Bahrain Surface Materials Resources Survey, 1976, and Brunsden et al, 1980, carried out a further survey at a reconnaissance level, and produced five reports covering the significant aspects of geomorphology, geology and pedology of Bahrain, together with more accurate geological and geomorphological maps on a scale of 1:10,000. In the report on the geology, a revised stratigraphy for Bahrain was erected (Table 1.1.a). The units erected in this stratigraphy were correlated with those of Willis, 1967, (Table 1.1.c) and Powers et al, 1966, and Cavelier, 1975, (Table 1.1.b) and B.S.M.R.S., 1976, compared the bed thicknesses of their units with the same units in Saudi Arabia, finding that those of Bahrain are more than twice the thickness of the equivalent deposits in the Damman area (Fig. 1.4).

A complete account of all the previous work concerning the geology of Bahrain is given by Messrs. Sandbergs, 1975.

1.4 Bahrain:

Bahrain consists of thirteen islands and numerous small patches of land and coral reef, lying approximately at latitude 26°N and longitude $50^{\circ} 30'\text{E}$, in the Gulf of Salwa (Fig.1.1). The islands lie on the shelf area of Saudi Arabia, known as the Hasa Terrace, and are surrounded by shallow water which rarely exceeds 18m. in depth. The islands lie in the core of an extensive arid area.

SYSTEM	SERIES	STAGE	FORMATION IN BAHRAIN
NEOGENE	Holocene		Superficial sediments and soils
	Pleistocene		----- Ra's al 'Aqr Formation
	Pliocene		
	Miocene	Messinian Tortonian Serravallian Langhian Burdigalian Aquitian	~~~~~ Jabal Cap Formation
	Oligocene		
PALAEOGENE		Bartonian Auversian	~~~~~
	Eocene	Lutetian	Jabal Hisai Carbonate West Rifa Flint Al Buhayr Carbonate Foraminiferal Carbonate
		Ypresian	Dil 'Rafah Carbonate Hafirah Carbonate Awali Carbonate
	Palaeocene	Thanetian Montian	(Umm er Radhuma Formation)

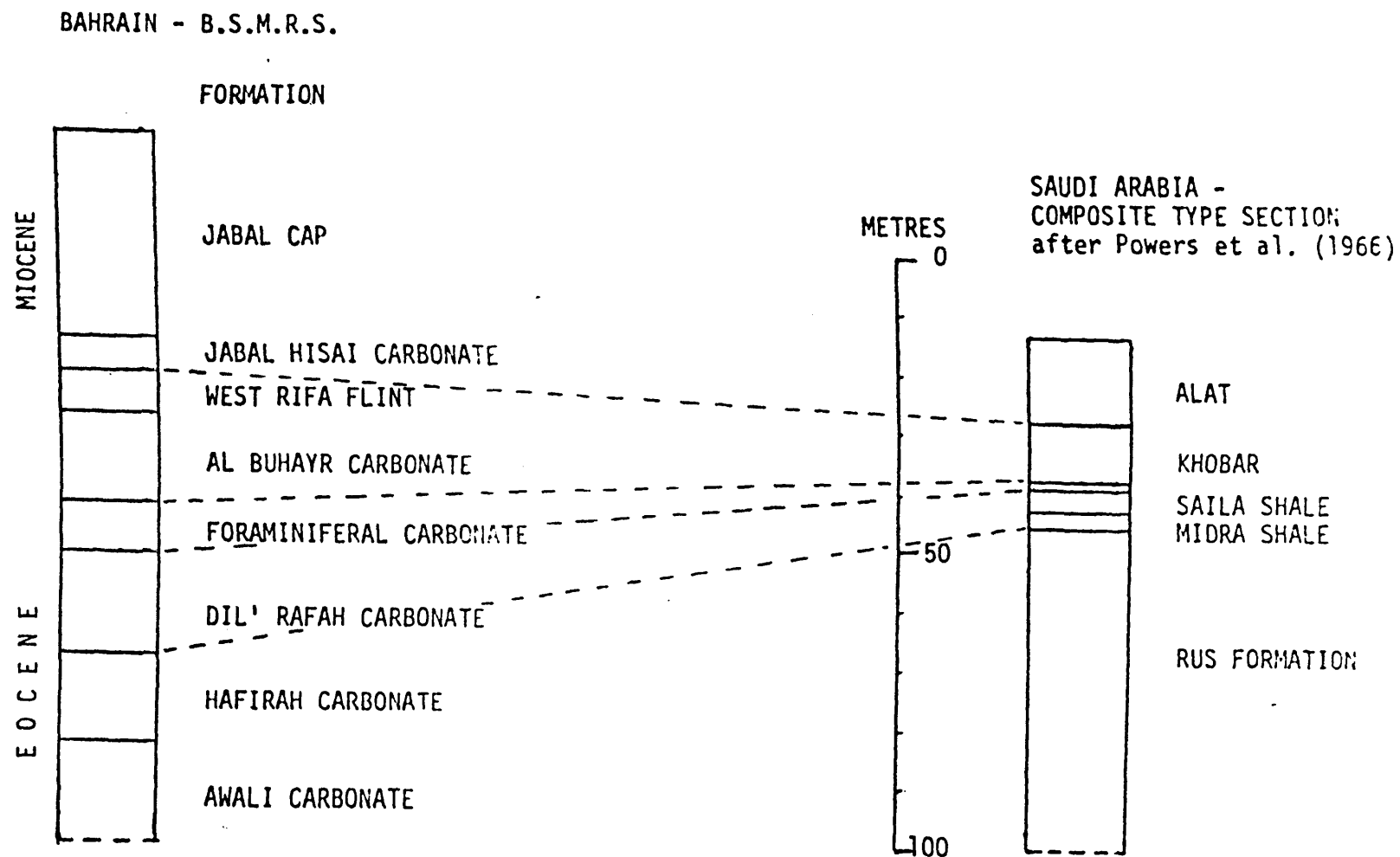
Table 1.1.a Stratigraphic column for the Cainozoic strata of Bahrain (after Brunnsden et al, 1980).

	DAMMAM Powers <i>et al.</i> 1966; Theil 1973	BAHRAIN (this work)	QATAR Cavelier 1975
MIOCENE	Dam Formation	Jabal Cap Formation	(Lower Fars Formation)
EOCENE	Damman Group	Jabal Hisai Carbonate West Rifa Flint	
		~~~~~	
		Al Buhayr Carbonate Foraminiferal Carbonate	Abarug Member Umm Bab Member Dukhan <i>Alveolina</i> Limestone Member Midra (and Sada) Shales Member Rujm Al'd Ulatay Limestone Member
	Rus Group	Dil 'Rafah Carbonate	
	Limestone (member) Marl and Limestone (member) Limestone (member)	Hafirah Carbonate Awali Carbonate	Rus Formation
	Umm er Radhuma Formation	(not present at surface)	Umm er Radhuma Formation

Table 1.1.b Lithostratigraphic correlation of the Eocene and Miocene of Bahrain with those Saudi Arabia and Qatar (after Brunnsden et al, 1980).

	Willis (1967)	This Survey	
Dammam Formation	White Limestone Orange Marl Brown Crystalline Limestone Shark's Tooth Shale	Jabal Hisai Carbonate Formation West Rifa Flint Formation Al Buhayr Carbonate Formation Foraminiferal Carbonate Formation Dil 'Rafah Carbonate Formation	Dammam Group
Rus Formation	Rus	Hafirah Carbonate Formation Awali Carbonate Formation	Rus Group

Table 1.1.c An approximate correlation between the Eocene divisions used by Willis, 1967, and those used by Brunnsden et al, 1980 (after Brunnsden et al, 1980).



N.B. These are minimum thicknesses  
as the tops of some of the  
Formations were not seen.

Fig. 1.4 Comparison of bed thicknesses between Bahrain and Saudi Arabia (after B.S.M.R.S., 1976).

The following is a brief review of the stratigraphy, structure, geomorphology and depositional history of the Tertiary and Quaternary periods in Bahrain.

#### 1.4.1 Stratigraphy:

The stratigraphy succession adopted in this thesis is that developed by B.S.M.R.S., 1976, from Willis's provisional correlations. The following is a brief account of this succession (for their distribution in Bahrain see Figs. 1.5 and 1.6).

In the following discussion it should be noted that dolomitization of the Eocene strata is dominant at the surface, while in some areas, with depth, dedolomitization occurs, Brunsden et al, 1980, state that stratigraphic and isotopic evidence both point to the dolomitization and dedolomitization having taken place in a fresh-water environment.

##### 1.4.1.I The Eocene:

The rock units of the Eocene are the base of the succession which has been recognised and defined from the rocks exposed at the surface of Bahrain. The Eocene rocks have been subdivided into three units; the Umm er Radhuma group, the Rus group and the Damman group (Table 1.1.a).

##### A. The Umm er Radhuma Group:

Italconsult, 1971, suggested that the Umm er Radhuma Formation might outcrop in Bahrain, but no localities, nor means of distinguishing this formation were given. B.S.M.R.S., 1976, could not recognise this unit in surface outcrop, but the overlying Rus Group was identified, and it was suggested that the lower part of the Rus (the Awali Carbonate Formation) may prove, after more detailed study, to be more appropriately correlated with the Umm er Radhuma Formation in Saudi Arabia.

##### B. The Rus Group:

In Saudi Arabia, the Rus Group cannot be dated, however, the overlying and underlying formations have been dated palaeontologically thus giving the Rus an Ypresian age (Lower Eocene). In Bahrain, Willis, 1967, classified all the rocks cropping out below the first shale horizon which marks the base of the Damman Group as the Rus Formation (Table 1.1.c). B.S.M.R.S., 1976, promoted this unit to group status and divided it into two formations making the division at a prominent hard band characterised by Lithophaga borings. The two identified formations are the Awali Carbonate formation

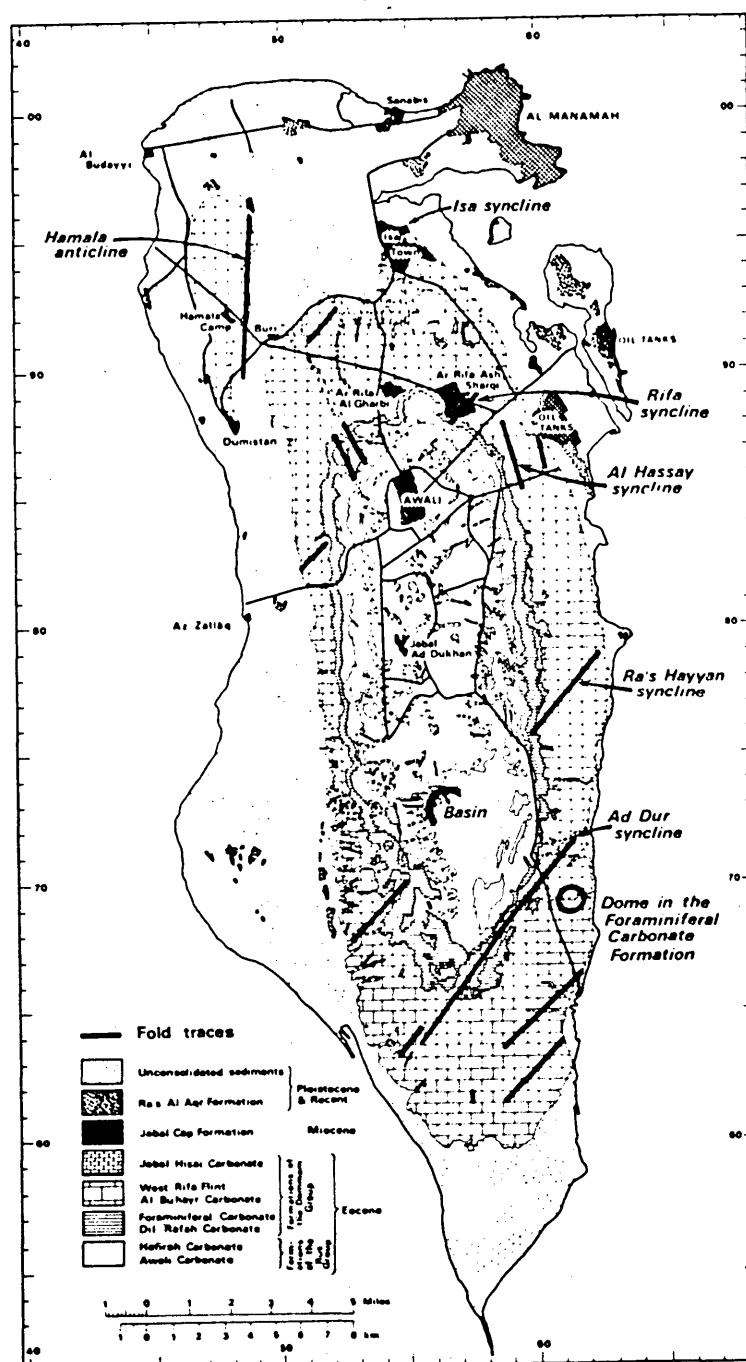


Fig. 1.5 Geologic and structural map of Bahrain (after Brunnsden et al, 1980).

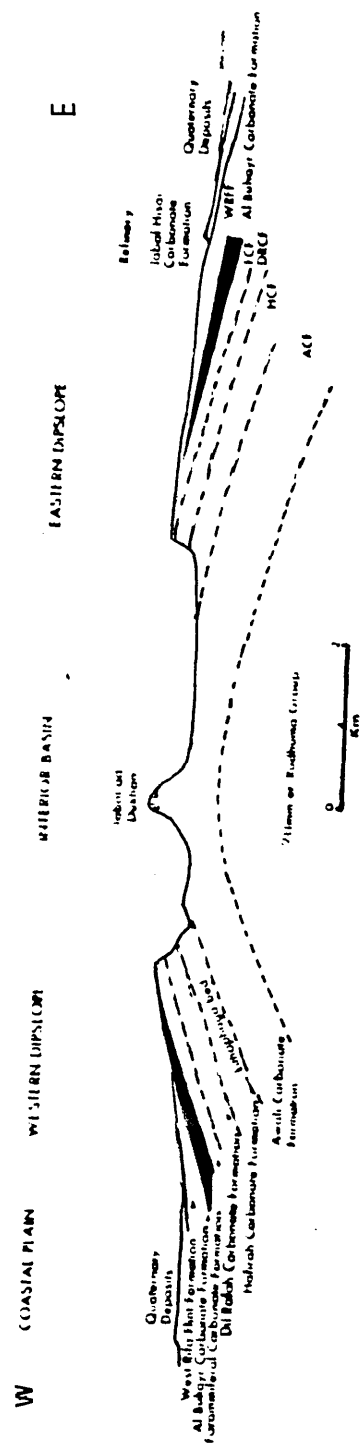


Fig. 1.6 The distribution of the Cretaceous strata of Bahrain (after Brunson et al, 1980).

and the Hafirah Carbonate formation.

a). The Awali Carbonate Formation:

This unit is the lower of the two units of the Rus, and occurs below the Lithophaga bored hard band as gently dipping thick beds, with occasional medium thickness beds. The rocks making up this unit are mainly dolosiltites with small, but variable, amounts of quartz and clay minerals. Relatively hard bands showing indurated infillings of crustacean burrows occur. At several horizons bands of quartz geodes after anhydrite nodules also occur and at other horizons dense black flinty cherts are present. The presence of the geodes indicates the evaporative nature of the beds.

The top of the unit is a laterally persistent hard band (0,5m. thick) characterised by Lithophaga borings. This is the unit which divides the Rus into its two formations and is a yellowish brown dolomitic arenite with its upper surface covered with vertical Molluscan borings.

b). The Hafirah Carbonate Formation:

This unit occurs above the Lithophaga hard band, and much of of its area of outcrop is obscured by extensive spreads of Recent alluvium and hillwash, the beds are of medium thickness becoming very thick towards the top of the sequence. The rocks in this unit are mainly dolosiltites and dolochalks. The lithologies of the lower part of the formation are similar to those of the Awali Carbonate, with irregularly cemented crustacean burrows and geodes. The rocks forming the upper part of this formation are similar to those forming the lower part Awali Carbonate, being massive dolomites interrupted by horizons of crustacean burrows. The burrows are filled with coarse grained dolomite.

No body fossils, which could have aided in establishing the age of these units, have been found in either the Awali or Hafirah Carbonate Formations.

C. The Damman Group:

The first shale has been taken as the base of the Damman Group, and the group extends to the Eocene Miocene Contact. The group is divided into five formations, these are:

a). Dil'Rafah Carbonate Formation:

The Dil'Rafah Carbonate Formation consists of an alternating series of deposits of dolosiltites and attapulgitic-rich shales or clays, with the carbonates being dominant, and the first shale horizon being taken as the base of the unit. The carbonate beds are mainly thin to medium in thickness, while the clay beds are thin to very thin, apart from a medium clay bed at the top of the formation which is characterised by abundant oyster shells. The shales and dolomites form a rhythmic sequence of sedimentary units which is repeated eight times; each shale unit is followed by a dolosiltite which is capped by finely bedded or laminated dolomite in which desiccation cracks and soil structures are present, indicating exposure above sea level.

b). Foraminiferal Carbonate Formation:

The Foraminiferal Carbonate Formation consists of calcilutites and bioclastic calcarenites rich in forams, with a carbonate matrix, all of which have been dolomitised. The unit is thickly to very thickly bedded and is more massive than the underlying units, and marine body fossils occur. This unit together with the underlying Oyster-bed, marks the commencement of a new sedimentological regime in the Eocene of Bahrain, with the absence of oscillation of the depositional surface above and below sea level and the absence of finely laminated carbonate rocks.

c). Al Buhayr Carbonate Formation:

The base of the Al Buhayr Carbonate Formation is a laminated, rusty, yellowish orange argillaceous dolosiltite, with occasional clay pockets. Above the yellow marker band lies a carbonate unit, which is dolomitised at outcrop. At some localities where the carbonate is exposed at the surface by the stripping away of the superficial material, the rock has frequently been altered to a hard compact saccharoidal silicified dolomite, locally termed "blue askar". The Al Buhayr unit is thickly bedded, and it is extensively burrowed, but the unit has not been homogenised. The upper few metres of the formation are more thinly bedded.

Body fossils are common in the lower part of the unit. At some localities the unit is completely eroded, and the West Rifa Flint Formation rests directly on the Foraminiferal Carbonate Formation.

d). West Rifa Flint Formation:

The West Rifa Flint Formation is distinguished from the Al Buhayr Carbonate Formation by the presence of abundant flints. It consists of thin to medium bedded dolomite containing layers of brown or black tabular flints arranged parallel to the bedding, at intervals of 0.2m. to 0.3m. Where the overlying superficial materials have been removed, the unit seems to be altered to "blue askar". In the absence of flint, this unit is similar to Al Buhayr Carbonate Formation.

e). Jabal Hisai Carbonate Formation:

The base of the Jabal Hisai Carbonate Formation has not been identified in Bahrain. The main part of the unit is distinguished by its echinoid-rich fauna and is composed of dolosiltites containing darker stained crustacean burrow infillings, especially near the top which is highly fossiliferous and coarser grained.

1.4.1.II The Miocene:

The Miocene rocks of Bahrain, the Jabal Cap Formation, lie unconformably on rocks of the Rus Group. Willis, 1967, believed this unit to be part of the Eocene.

Jabal Cap Formation:

This Jabal Cap Formation is a massive caprock which has locally preserved the underlying Rus Group from erosion. Just below the caprock, rocks of the Hafirah Carbonate Formation are overlain by a conglomerate containing rounded to angular boulders of dolomite and rare rounded flint pebbles in a carbonate matrix. The sediments of the main part of the caprock consist of dolomite which has a fine laminated structure, sometimes flat, but more often shaped into rounded cauliflower-like structures which are formed by coral, red algae and hydrozoans. The rocks are frequently bored by Lithophaga. Also associated with these deposits are breccias composed of algal and coral fragments and interbedded spreads of cross-bedded arenites. The dolomitic arenites may pass up into calcilutites showing desiccation cracks.

All the rock types represented in this unit indicate deposition under very shallow water conditions. Microfossils from this unit have been attributed to the Neogene (possibly Upper Miocene, but a younger age is not precluded).

### 1.4.1.III The Pleistocene

#### A. Ra's al'Aqr Formation:

The base of this formation is not seen, but the formation consists of three units, which at different localities may have local variants in the assemblages of rock types.

##### a). Calcisiltites:

This is the lowest unit and the rocks of this unit are thinly bedded (10-20mm.) and are composed of fine to very fine-grained dolomite calcisiltites. Some layers are rich in Lamellibranch shells which are lying with their convex side up. In some localities, coarser dolomitic arenites are interbedded in this unit.

##### b). Mudflood deposits:

This is the middle unit, and it is composed of a conglomeratic dolosiltite, conglomeratic material is more abundant near the base. Below the conglomeratic dolosiltite, there is a thin sandy deposit which has risen in places through the conglomeratic dolosiltite to form sand volcanoes.

##### c). Caprock Limestone:

This is the top unit, and is composed of thin bedded quartzose shelly oolitic limestone. The shells are frequently those of cerithid gastropods.

#### B. Aeolianites:

These have been described by Willis, 1967, as miliolites, but are aeolianites which are cross-bedded, loosely cemented, oolitic quartz arenite, containing abundant forams and small shells. They are Pleistocene in age, and are found as small eroded outcrops throughout the island and are relics of a once more extensive deposit.

#### C. Unconsolidated deposits:

They are deposits of Pleistocene to Recent age and have a wide range of origins. Several geomorphic units exist e.g. ridges, sabkha, playa, saltpan, accretion zone, platform, dunes and nebkhas, etc. The sediments are mainly composed of quartz with lesser amounts of carbonates, gypsum and anhydrite, but in some geomorphic units carbonates or gypsum and anhydrite may dominate.

#### 1.4.2 Structure:

As previously mentioned in section 1.2.3., Kassler( 1973) visualises Bahrain as part of a structural complex of N-S Arabian trend structures, deformed slightly by NW - SE Zagros trend folds.

At the moment the amount and mechanism of movements of the slow uplift of Bahrain and the tilting of the Arabian Homocline over the last 6,000 years are not fully understood.

The view adopted in this thesis is that originated by the B.S.M.R.S., 1976; that the main structure of the island of Bahrain is dominated by a highly elongated asymmetrical dome structure (beds dipping more steeply to the west) formed of Eocene rocks dipping gently outwards at angles less than  $1^{\circ}$  towards the margins of the island. The Eocene rocks forming the dome are surrounded by flat, low-lying superficial deposits of Pleistocene to Recent age, forming extensive areas which are not affected by the updoming (Fig.1.6). The dome is elongated in a N-S trend, the long axis being about three times the width.

Bahrain and analogous updomed areas are underlain at great depth by broad salt domes forming swells with a N-S elongation which are responsible for the updoming of the rocks at the surface. The dome was formed of the Foraminiferal Carbonate, Al Buhayr Carbonate and West Rifa Flint Formations. The crest of the dome was later removed by erosion exposing the older rocks in the core of the dome and the Miocene Jabal Cap Formation was deposited on this eroded surface, later further erosion produced an interior basin enclosed by an almost continuous escarpment. The Al Buhayr and West Rifa Flint Formations form extensive dipslopes on the back of the escarpment, sloping down gently to the east and west and covering broad areas in the north and south of the island.

Bedding traces on the dipslope of the main dome reveal a complex structure which is not related to the main dome. The bedding traces outline a series of very sharply defined synclines trending mostly from NE to SW, oblique to the trend of the main dome structure and extending across the island at intervals of about 5Km. Six synclines have been recognised (Fig.1.5), five of them have a NE - SW trend, while the sixth has a N-S trend.

These folds are not due to compression, but represent the surface expression of faults at a shallow depth in underlying rocks. These faults are normal faults with a downthrow towards the cores of the synclines, across which the overlying beds have been draped to form a monoclinial fold. The faults occur in pairs, forming small rift systems having a NE - SW trend. A local complementary N-S set of faults has also developed.

B.S.M.R.S. (1976) suggests that the faults and their associated synclines were formed before the development of the main dome structure.

Some of the traces on the dipslope do not represent bedding traces, but joint traces. The predominant joint trend is N - NE to S - SW, this joint set has frequently provided zones of weakness for erosion and is often followed by drainage courses, and has influenced the development of the escarpment.

A few small dome structures with gentle outward dips exist at the southern and northern parts of the island (Fig.1.5). These domes are due to local movements in the rock beneath which contains evaporites.

In the northern part of the island there is an anticline, the Hamala Anticline (Fig.1.5), which is asymmetrical with its steeper limb towards the east. The core of the anticline is composed of yellow siltstone at the base of the Al Buhayr Carbonate Formation, overlain by the Al Buhayr and West Rifa Flint Formations.

#### 1.4.3 Geomorphology:

The relief of the island is generally low, the highest point being 122.4m., and well over half the surface is below 20m. Nevertheless, five major physiographic regions which occur as concentric belts can be identified (Figs.1.7 and 1.8), these are:

- a. The Central or Ar Rumanum Plateau and Jabals.
- b. The Interior Basin.
- c. The Multiple Escarpment Zone.
- d. The Upper Dammam Backslope.
- e. The Coastal Lowlands.

Denudation led to the development of this essentially simple pattern of concentric oval outcrops, which form the core of the island around

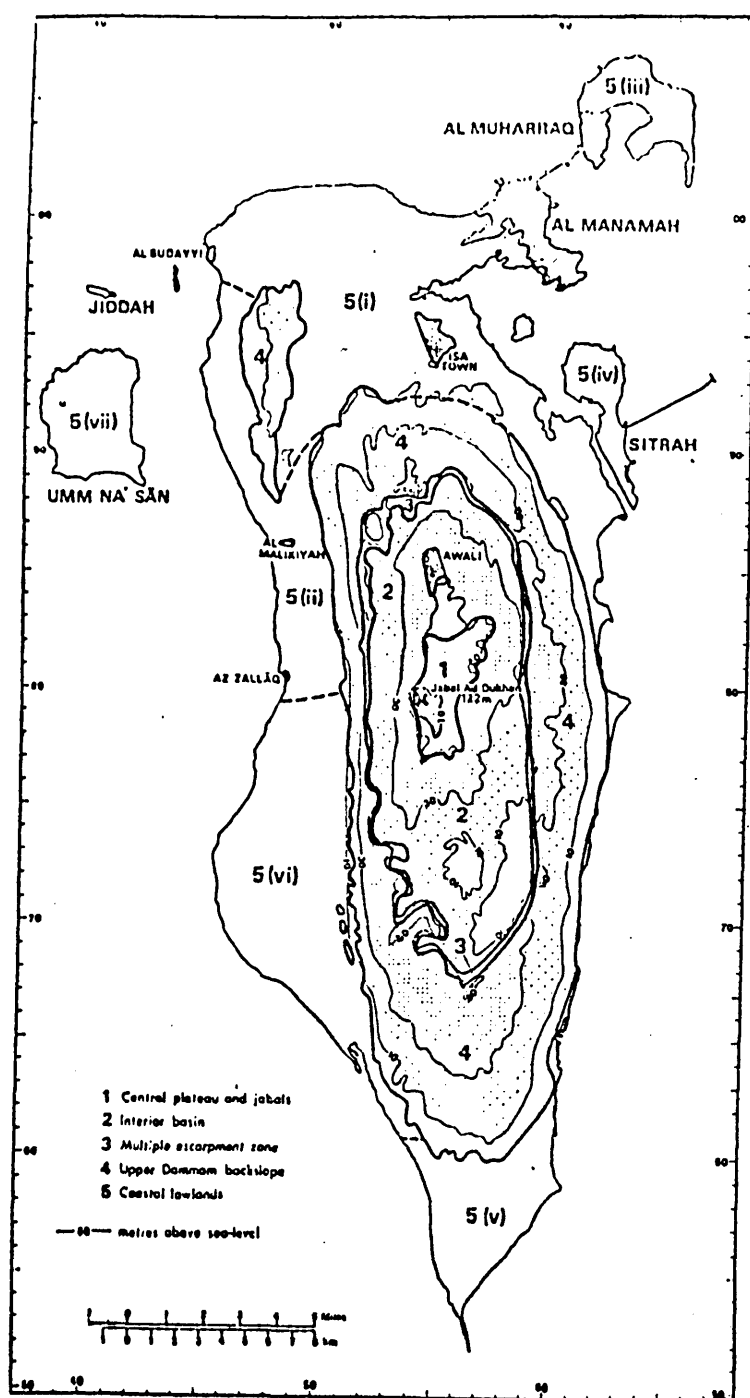


Fig. 1.7 A regional subdivision of Bahrain (after Brunsten et al, 1980).

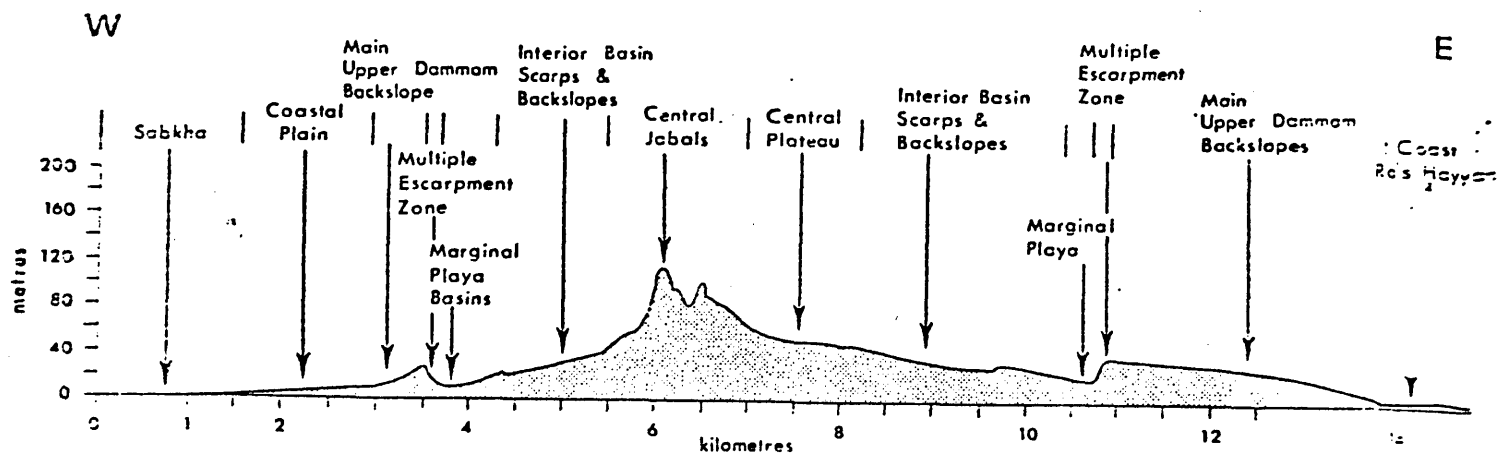


Fig. 1.8 A cross section of Bahrain showing the main physiographic regions and the asymmetry of the relief (after Brunsten et al, 1980).

which occurs a fringe of Recent coastal sediments of variable width. The coastal sediments are subdivided into geomorphic units.

The extreme simplicity of this bedrock outcrop pattern is modified by several factors; firstly the major structure forming the island is asymmetrical in an E-W direction, the dips being slightly steeper in the west thus resulting in a narrowing of the outcrop there. Secondly a number of minor synclines and anticlines cause local increases in dip, and repetition in both topographic and outcrop patterns. Finally, some of the coastal and unconsolidated sediments fringing the island are due to their accumulation against Tertiary and Pleistocene strata which were either not deposited over the central parts of the island or have subsequently been destroyed by erosion.

This geomorphological situation has not always been the same as is shown in the next section, the geological evolution of Bahrain.

#### 1.4.4 The Geological Evolution of Bahrain:

A crystalline basement of metamorphic and igneous rocks similar to those of the Arabian Shield lies at approximately 3.5Km. below Bahrain and is more than 600 million years old.

The oldest exposed rocks on the surface of Bahrain are of Eocene age (ca. 60 million years old). Since the Eocene the surface of Bahrain has always been near sea level; sometimes just below and sometimes just above sea level. During this period, 170m. of calcareous sediment has accumulated and the basement has subsided to accomodate this thickness of sediments.

The Rus Group was deposited as soft carbonate muds in shallow water and the sediments were burrowed. A hard ground bored by Lithophaga separates the Awali and Hafirah Carbonate Formations, indicating a pause in sediment deposition and lithification of the surface sediments shortly after their formation. The presence of desiccation cracks and geodes indicates exposure above sea level. Geodes were formed by partial replacement ^{and dissolution} of anhydrite, and anhydrite indicates evaporation of sulphate-rich waters under subaerial conditions.

The Dil'Rafah Carbonate Formation rests conformably on the Rus, and the sediment types indicate that it too was deposited from just below to just above sea level. The sediments thin towards the crest

of the dome from both flanks indicating that the dome structure was already developing during the deposition of these sediments, and that non-deposition and erosion occurred more frequently over the crest of the dome.

The sediments of the Foraminiferal Carbonate Formation suggest a change of environment, as the water became deeper and had a more direct connection with the open sea.

The yellow siltstones and soils at the bottom of Al Buhayr Carbonate Formation indicate emergence above sea level followed by deposition of silty carbonate sediments in the intertidal - subtidal zone. The dome continued developing, and erosion was also more frequent at the crest of the dome, sometimes leading to complete erosion of the unit, and where this occurred, the West Rifa Flint Formation rests unconformably on the Foraminiferal Carbonate Formation.

Jabal Hisai Carbonate Formation is deposited in deeper water with a more direct access to the open sea. After deposition of this unit, deposition of sediments ceased, and no deposits in the Upper Eocene or Oligocene are present. During this period of non-deposition faulting in the underlying rocks occurred and formed NE - SW synclines and the N-S complementary syncline. Following that, the rocks were folded into the dome structure, which was deeply eroded before the deposition of the Jabal Cap Formation.

The assemblage of sediments of the Jabal Cap Formation is indicative of deposition under shallow water, subtidal or intertidal conditions.

The deposits of the Ras al Aqr Formation are not tilted because they were deposited after the development of the dome structure. The deposits were laid down in shallow water near the shoreline.

### 1.5 Methods of Study:

As previously mentioned in 1.1, the fieldwork was carried out by members of the B.S.M.R.S. In the southwest sabkha, a considerable amount of information was obtained by means of air photograph interpretation, but the complexity of the surface features necessitated detailed surveying on foot. For a better understanding of the depositional sequence of this coastal complex, many shallow pits were dug^{and} the work was carried out on a reconnaissance level. The sediments of the pits were described (standard engineering geology terms were used, Q. Jl. Engng. Geol., 1972),

measured, photographed and sampled in order to assess their suitability as constructional materials. Some of the surface samples rich in gypsum and/or anhydrite were not sampled as they were irrelevant to the purpose of the B.S.M.R.S. project, but would have been very useful for the present study. This, plus the loss of some samples and the inability of the author to go to the field area and see the relationship between the different sedimentary units for himself, have been a major disadvantage.

It is hoped that the results of this study may aid further work on the area.

#### 1.5.1 Field Procedure:

This section is a summary of the fieldwork carried out by B.S.M.R.S., 1976.

Field investigations were generally preceded by an air-photo interpretation on a scale of 1:10,000. The fieldwork consisted of checking the air-photo interpretation, additional mapping and a heavy pitting programme on the coastal complex (for the pit locations see Fig.3.89).

Topographic surveying was achieved by two means; a control survey, including erection of marker beacons, and levelling.

The purpose of the control survey was to provide points where there was an absence of recognisable cultural features in the landscape (similar to the points of Evans et al, 1969, at Abu Dhabi). In the southwest sabkha, five points were marked by metal rods set in concrete blocks at ground level, with beacons about three metres high erected over them.

The purpose of levelling was to provide topographic profiles. This was carried out using a self-adjusting level by taking forward and backward sights to spirit levels, the sight length being made approximately equal by pacing, and corrected if the lengths calculated from stadia readings differed by more than two metres. The sight length was 35-50 metres depending on topography (reduced on steeper slopes), heat shimmer and wind.

Five profiles were surveyed (Fig.3.89). These were designed to cover

the area of study from N-S and E-W, and to establish the spatial relationship between all the individual morphological units present. These profiles also provided a base onto which chemical and compositional changes in the sediments and groundwater, and mineralogical changes in the sediments, could be plotted. Temporary bench marks, consisting of wooden pegs and/or painted marks on the ground, were placed at intervals of approximately one kilometre for later relocation of the profiles.

All the profiles on the southwest sabkha were related to an approximate high water mark (H.W.M.). This was taken at approximately 2.0 metres (all heights were reduced to Admiralty datum) in the light of the small rate of change of H.W.M. down the east coast (as judged from beach features, such as drift material). Where possible the pits were dug to a depth just below the groundwater table and the unconsolidated sediments were sampled (for location of samples along each profile see Fig.3.90).

If groundwaters were reached in pits, they were sampled and their levels measured. The air, surface and water temperatures were measured at some stations.

Sediment and water samples were shipped to London, where they were analysed and assessed as to their suitability for use as constructional material, and then stored in the geology department at Imperial College, London, until the initiation of this detailed study in 1978.

#### 1.5.2 Laboratory Procedure:

Details of analytical and experimental techniques will be given where they are not standard practice.

##### 1.5.2.I Sediment Preparation:

The object was to prepare sediments for petrographic, mineralogic and chemical studies.

Consolidated sediments and some selected, washed, sand grade, unconsolidated sediments were impregnated with Araldite resin AY18 and hardener HZ18 (the impregnated sediments were left to set in an oven for two days at 30°C. to prevent dehydration of gypseous sediments).

The unconsolidated sediments were split by the cone and quartering method, and four splits each weighing approximately 20 grams were

produced. One of the splits and what remained of the original sample were sealed and stored as reference samples.

One of the splits was further subdivided into sand and silt plus clay grades to facilitate the petrographic study of the coarse fraction without the hinderance of the silt plus clay. This was achieved by soaking the split in approximately one litre of water, stirring it and leaving it to soak for 24 hours. The soaked sediment was then stirred for ten minutes and wet sieved through a 0.0625mm. (240 mesh) sieve. The sand fraction was filtered and then left to dry on the filter paper in an oven at 40°C. The silt plus clay and the water with which it was washed were centrifuged and then the supernatant water was decanted. Due to the breakdown of the centrifuge, some of the silt plus clay fractions were allowed to settle and the excess water decanted. The silt plus clay fractions were also dried at 40°C. to prevent dehydration of gypsum.

A second split was treated as described above and then used for sieve analysis. But in this case both the sand and silt plus clay were weighed when dry.

The third split was soaked, stirred and left overnight. When the fine material had settled down the excess water was decanted and the sample was filtered and dried in an oven at 40°C. In this process both sand and silt plus clay were retained, but the soluble salts were dissolved and removed. When dry, the whole sample was ground in an agate Tema mill and the powder was ready for chemical analysis. For x-ray diffraction, this powder was further hand crushed in an agate mortar to ensure the right grain size and the homogeneity of the powder.

#### 1.5.2.II Petrographic Studies:

The sand grade material was studied using a binocular microscope. The size, sorting, colour, surface features, coating and bonding agents of each grain as well as the approximate percentage of grain types were recorded.

Thin sections of selected araldite impregnated unconsolidated and consolidated samples representing different units were studied using a standard petrographic microscope to determine the mineralogy of the sediments and the diagenetic changes they have undergone.

### 1.5.2.III Size Analysis by Sieving:

A set of British Standard sieves, ranging from  $-1.04 \phi$  (2.057mm.) to  $3.91 \phi$  (0.66mm.) at  $\frac{1}{4} \phi$  intervals was used. A constant time of 15 minutes using a Ro-Tap machine was found satisfactory for all the samples. Each sieve fraction was weighed to 0.0001g. accuracy.

The data obtained from grain size analysis were plotted by a computer programme developed by Dr. J. Ferguson of Imperial College, and statistical parameters of grain size were obtained using Folks method, Inmans method and the method of moments.

This analysis was carried out to observe the relations between the statistical parameters, the composition of the sediments and the sedimentary units.

### 1.5.2.IV Qualitative and Quantitative Mineralogy:

The qualitative and quantitative mineralogical compositions of the sediments were determined using x-ray diffraction methods. The samples were analysed using a Philips PW1050 powder diffractometer employing Fe filtered Co K $\alpha$  radiation. The samples were scanned over the range  $5^\circ$ - $65^\circ$   $2 \theta$  to include the principal and subsidiary peaks of clays, gypsum, anhydrite, quartz, celestite, feldspar, high and low magnesium calcite (calcite or low magnesium calcite will be used as having the same meaning in this text), aragonite, dolomite and magnesite.

The calculation of the percentage of the minerals in every sample was carried out using a computer programme (Cuff, 1972; Bush, 1973) based on the use of the height of the main diffraction peaks for each mineral. The accuracy of this method is reasonable ( $\pm 10\%$ ) if the analytical factors are kept constant i.e. the constancy of the method, and time of grinding of samples, and using the diffractometer under constant conditions.

### 1.5.2.V Chemical Analysis of Sediments:

#### a. Determination of CaCO₃ content:

Precise values for carbonate carbon were obtained using the method developed by Bush, 1970.

Duplicates were made to confirm the results. The accuracy of this

method gave the  $\text{CaCO}_3$  percentage, and enabled the author to back check the X.R.D. and Plasma results.

#### b. Major and Trace Element Analysis:

The Plasma spectrophotometer was used to investigate some major and minor trace elements (24 elements) in the sediments, some of which are presented in Appendix 3.

The sample and standards were prepared for the analysis as follows; 0.1 gram of powder was digested in 5ml. of 50%  $\text{HNO}_3$  acid, and then de-ionised water was added to the resultant to make it into 10ml. volume. Two blanks were also prepared.

To ensure that no gypsum or anhydrite reprecipitated, the supernatant

All the major mineral phases present apart from quartz were digested, however minor minerals like zircon, rutile, chromite and possibly baryte and celestite may well not have been attacked. See appendix III.

source unit was used. Inductivity coupling provides an optical emission spectrum which allows the elements present to be measured over wide ranges of concentration and down to very low trace levels very rapidly. A computer attached to the apparatus produces the major elements as percentages of their oxides, and the trace elements as parts per million (PPM). The analysis using the Plasma was carried out at King's College, London, in the Geology Department, under the supervision of Dr. N. Walsh.

A few samples could not be measured by the ICP as they contained concentrations of elements too high for accurate determination, so these samples were analysed by atomic absorption spectrophotometry.

The results obtained confirm the results of X.R.D. and carbonate content, and help explain the mineralogy of the sediments.

#### 1.5.2.VI Water Analysis:

The author found that precipitation of salts has occurred within the plastic bottle containers of the samples, so they were discarded. Fortunately, B.S.M.R.S., 1976, analysed the groundwater samples, and their results are those plotted by the author and used in this thesis. They determined the chemistry of the water samples giving emphasis to the major elements and using standard methods (Bush, 1973).

## CHAPTER TWO

Climate and Geomorphology of  
the area of Study.

## 2. The area of Study:

The coastal plain of Bahrain extends from the base of the Tertiary backslope (elevations less than 10m.) to the coastline (Fig.1.5). It covers an area of approximately 275Km.², topographic variation is generally less than 5m. and is developed in loose or partially cemented marine and aeolian sands which cloak an irregular foundation of Quaternary limestone and dolomite which is occasionally exposed.

The area of study, the southwest sabkha, extends from Az Zallaq in the north to Ras al Mumattalah in the south, covering an area of approximately 60Km.² (Fig.2.2).

This wide Quaternary coastal bulge widens to about 6Km. and becomes generally lower in elevation south of Az Zallaq, to narrow again south of Ras al Jazair until inshore of the Dawhat al Mumattalah is less than 1Km. wide where it is formed of a beach ridge complex which links the southwest sabkha to the south sabkha, and extends south to Ras al Barr without a break. The surface of the sabkha is generally less than 3m. high, with large areas lying below A.H.W.M. e.g. Mamlahat al Mumattalah (the salt pan). These areas are subject to inundation during storms and/or after heavy local precipitation. The maximum elevation is approximately 6m. and occurs in the dune fields around Adaim and Al Markh (See Fig. 2.2).

East and southeast of Al Jazair, thinly veneered or bare rock pavements of Quaternary limestone outcrop. The depth of the unconsolidated sediments overlying them is unknown, but is probably not great.

The surface of the sabkha is devoid of vegetation apart from a sparse cover of halophytic plants on the dunes, nebkhas and beach ridges.

### 2.1 Climate:

Climate plays an important role either directly or indirectly (e.g. by producing waves, currents, etc.) in controlling the configuration of the coastal areas, the topography of nearshore areas and the distribution and type of sediments.

The climate of Bahrain is fairly typical of that of the Arabian Gulf, having high temperatures, low and variable rainfall, predominant "Shamal" winds blowing N-NW to W-NW which are persistent and strong. Fog and dew are common, and potential evapotranspiration is high. All

these climatic factors show Bahrain to be extremely arid and it must be classified as a true desert (B.S.M.R.S., 1976).

Climatic data has been collected for several years by International Aeradio Limited for Bahrain International Airport, Al Muharraq (Tables 2.1 and 2.2), and in the Persian Gulf Pilot (tenth edition, 1955). This data will be taken to represent Bahrain since it is the only available data.

#### 2.1.1 Temperature:

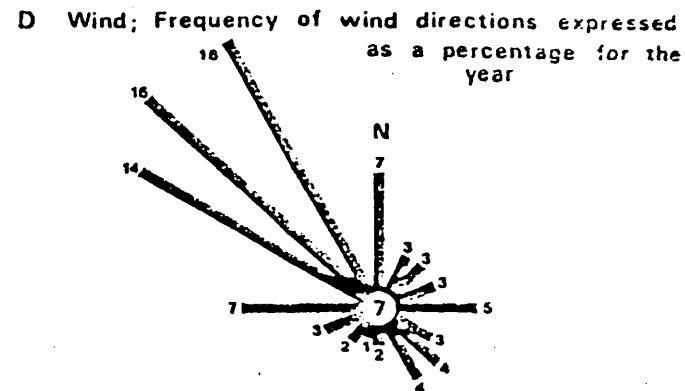
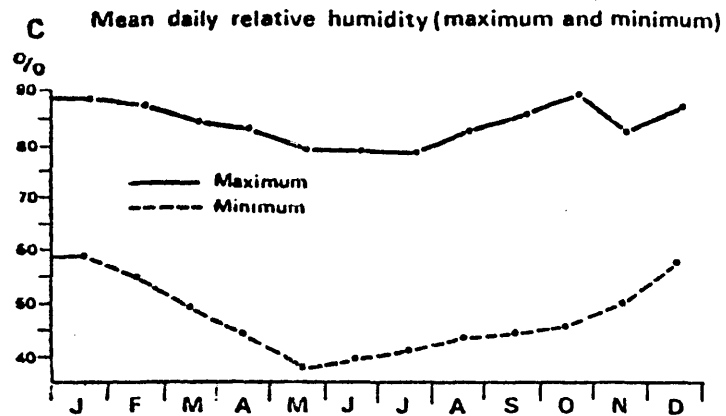
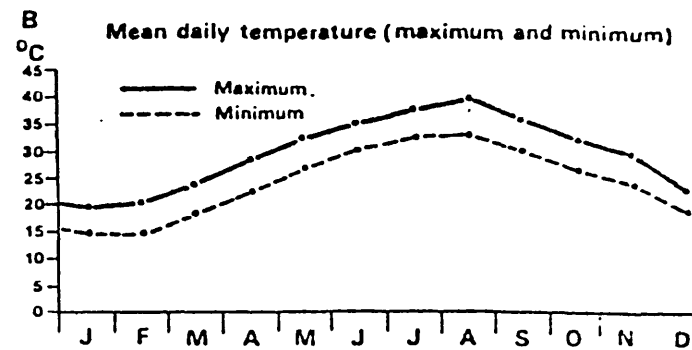
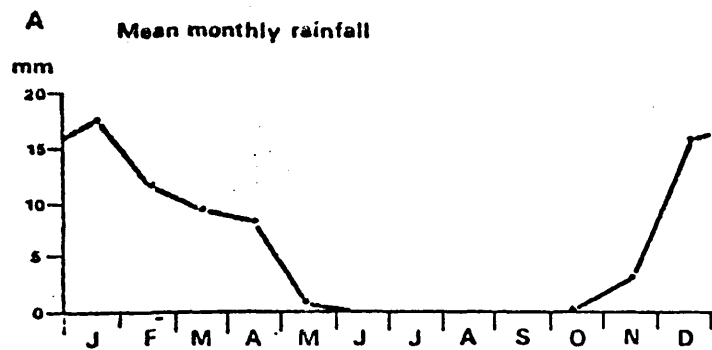
In Bahrain (Table 2.1 and Fig.2.1) the mean annual air temperature is about 27°C. This includes an annual variation from a mean daily minimum in January of 14°C. to a mean daily maximum of 38°C. in August. The diurnal difference between the mean daily maximum and minimum is nearly constant throughout the year (Fig.2.1). In spite of the high temperatures in Bahrain, there is a definite winter season, but frost is generally absent.

Temperature has a great effect on the flora and fauna, and on sedimentation and diagenetic processes. High temperatures result in high rates of organic metabolism (Gunter, 1957), reduction in the solubility of  $\text{CaCO}_3$ , leading to their precipitation, and changes in the chemistry of waters.

#### 2.1.2 Rainfall:

The rainfall is low and infrequent, but when it occurs it is often torrential; the average annual rainfall is 72.5mm. (this includes a range from 1.6mm. for 1946 to 168.9mm. for 1959) and throughout the year the amount of precipitation varies (Table 2.1 and Fig.2.1). June and August have no recorded rainfall, while July, September and October have trace amounts and from November amounts build up reaching 16.3 - 17.8mm. in December and January. Amounts decrease steadily from February to May from 12.2mm. to 1.6mm.

On average, Bahrain experiences 10 rainstorms of over 1mm. annually (B.S.M.R.S., 1976). They are heavy and of short duration and often occur locally. If the rainstorms are accompanied by gales, extensive flooding of flat, low-lying and enclosed areas will occur. Away from the coast, the effect will be a rapid production of surface run-off, and streams will experience flashy discharge leading to flooding of



Data supplied by International Aeradio Ltd., Bahrain International Airport.

Fig. 2.1 Summary of climatic data for Bahrain International Airport (after Brunsden et al, 1980).

	J	F	M	A	M	J	J	A	S	O	35 N	D	PERIOD Years
Mean daily maximum temperature °C	19.9	20.9	24.6	29.0	33.3	35.7	37.3	37.7	35.9	32.4	27.4	27.4	29
Mean daily minimum temperature °C	14.3	15.1	18.1	21.6	26.0	29.0	30.5	30.7	28.8	25.5	21.6	16.6	29
Highest maximum recorded	31.7	34.7	38.0	41.7	46.7	44.8	44.0	45.0	42.2	40.6	35.0	29.4	29
Lowest minimum recorded	2.8	7.2	7.8	13.9	18.7	22.7	25.3	27.4	24.4	20.6	13.5	6.4	29
Mean daily maximum wet bulb temp.	15.8	16.5	18.8	21.6	25.0	27.3	28.8	30.1	28.5	26.1	21.7	17.6	13
Highest wet bulb temp. recorded	21.1	22.2	23.9	27.6	30.6	32.1	32.2	34.0	31.8	30.0	28.5	21.9	13
Mean daily max. relative humidity	88%	87%	85%	83%	80%	80%	80%	84%	86%	90%	84%	88%	16
Mean daily min. relative humidity	59%	55%	50%	45%	39%	40%	41%	44%	45%	46%	52%	58%	16
Mean daily MSL pressure (mb)	1018.4	1017.1	1013.8	1010.8	1006.8	1000.9	997.4	999.0	1004.6	1011.8	1016.4	1018.2	44
Mean daily vapour pressure (mb)	14.8	15.2	16.9	20.3	25.2	27.9	31.8	34.7	32.1	27.2	21.7	17.1	44
Mean daily hours of sunshine	7.2	8.2	8.2	8.5	10.3	11.8	11.3	11.0	10.7	10.1	8.9	7.7	7
Mean monthly rainfall (mm)	17.8	12.2	9.7	8.9	1.6	0.0	*	0.0	*	0.3	3.2	16.3	29
Mean no. of rain days (1mm or more)	2.0	1.9	1.8	1.3	0.9	Nil	Nil	Nil	Nil	*	0.9	1.8	29
Highest rainfall in one day	54.8	29.4	18.6	64.0	8.0	0.0	*	0.0	*	8.9	13.5	42.7	29
Mean no. of days per month with:													
Fog (Vis. 1km or less)	1.7	0.8	0.5	0.1	0.2	0.2	0.2	0.1	*	0.7	0.8	1.0	29
Thick haze (Vis. 1km or less)	0.1	0.3	0.6	0.7	0.5	1.6	1.6	0.2	0.3	0.1	0.0	0.2	29
Thunder	1.2	0.9	1.8	2.0	1.0	0.0	0.0	0.0	0.0	0.1	1.2	0.8	29

NOTE:- *Indicates less than 0.05

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Table 2.1 Summary of climatic data for Bahrain International Airport  
(after Brunnsden et al, 1980).

Frequency of wind direction expressed as a percentage																	
	Calm	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Jan	7	3	1	2	1	3	4	8	7	3	1	1	2	8	20	17	12
Feb	5	5	3	1	2	6	4	7	6	2	1	1	1	4	14	18	20
Mar	6	8	3	3	3	7	6	6	5	2	1	1	2	4	8	16	19
Apr	4	11	5	4	6	8	6	5	5	3	2	2	3	4	7	11	15
May	5	11	4	4	4	4	3	2	4	2	1	1	3	7	11	16	18
June	5	8	3	2	1	2	1	1	1	1	2	2	4	8	17	20	22
July	6	8	4	4	4	5	2	3	2	1	1	3	4	8	13	18	14
Aug	9	8	4	4	4	4	2	3	2	2	1	2	3	8	14	17	13
Sep	9	8	5	3	3	4	2	2	2	1	2	2	3	7	14	16	17
Oct	9	9	4	4	4	6	3	3	3	1	1	2	2	6	13	14	16
Nov	7	5	3	2	3	5	4	5	6	3	2	1	2	7	16	15	14
Dec	9	3	1	1	2	2	3	4	6	3	1	1	2	10	26	17	9
Year	7	7	3	3	3	5	3	4	4	2	1	2	3	7	14	16	16

MEAN WIND SPEED IN KM/ HR.																	
MONTH	Calm	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
JAN	0	16.7	11.1	11.1	9.3	13.0	14.8	18.5	16.7	13.0	16.7	9.3	11.1	18.5	22.2	22.2	22.2
FEB	0	16.7	13.0	13.0	13.0	16.7	16.7	16.7	16.7	14.8	11.1	11.1	11.1	14.8	20.4	24.1	25.9
MAR	0	18.5	14.8	13.0	16.7	16.7	18.5	16.7	14.8	16.7	14.8	13.0	13.0	14.8	18.5	24.1	25.9
APR	0	20.4	16.7	14.8	14.8	18.5	16.7	16.7	14.8	13.0	11.1	13.0	13.0	13.0	18.5	22.2	25.9
MAY	0	18.5	14.8	13.0	14.8	16.7	13.0	14.8	13.0	13.0	13.0	11.1	11.1	13.0	16.7	22.2	24.1
JUNE	0	18.5	13.0	11.1	13.0	13.0	9.3	13.0	11.1	11.1	7.4	11.1	11.1	13.0	13.5	25.9	25.9
JULY	0	16.7	13.0	13.0	13.0	14.8	11.1	13.0	11.1	9.3	7.4	11.1	11.1	14.8	18.5	22.2	22.2
AUG	0	14.8	13.0	13.0	14.8	14.8	11.1	11.1	11.1	11.1	9.3	7.4	9.3	13.0	16.9	18.5	18.5
SEP	0	13.0	11.1	11.1	13.0	11.1	11.1	11.1	9.3	9.3	9.3	11.1	11.1	13.0	16.7	18.5	20.4
OCT	0	14.8	11.1	11.1	13.0	13.0	11.1	13.0	13.0	11.1	11.1	11.1	11.1	13.0	16.7	20.4	22.2
NOV	0	13.0	11.1	11.1	13.0	14.8	13.0	14.8	14.8	14.8	13.0	9.3	11.1	18.5	20.4	20.4	20.4
DEC	0	16.7	13.0	13.0	13.0	13.0	14.8	14.8	16.7	13.0	11.1	11.1	13.0	18.5	22.2	22.2	20.4
YEAR	0	16.7	13.0	13.0	13.0	14.8	13.0	14.8	13.0	13.0	11.1	11.1	11.1	14.8	18.5	22.2	22.2

MAXIMUM GUST IN KM/ HR.											
JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.
94.5	81.5	87.0	111.0	72.2	72.2	83.3	72.2	53.7	72.2	83.3	75.9

Table 2.2 Summary of surface wind data for Bahrain International Airport  
for 14 years based on observations made at 00 00, 06 00, 12 00 and 18 00 GMT  
'after Brunnsden et al, 1980'.

low-lying areas,

Rainwater may flush capillary waters from upper levels of the low-lying areas and dissolve away the surface crust. While towards the escarpment the effect will be erosion, entrainment and transport of loose deposits, and their subsequent deposition in low areas.

### 2.1.3 Wind:

The analysis of wind direction and strength is important as it plays a major role in modifying the coastline and inland areas.

The predominant wind directions have a northwesterly component (the Shamal), and this is also the direction from which the strongest winds blow (Fig.2.1 and Table 2.2). Over the whole year, 46% of the winds come either from the WNW, NW or NNW. The next two most frequent directions are those from the N and W (Fig.2.1). The other directions are almost equally represented throughout the year.

Mean wind speeds are approximately 11.1 - 14.8Km/hr. in all directions apart from those from the WNW, NW and NNW which have mean speeds of 18.5, 22.2 and 22.2Km/hr. respectively (Table 2.2). This confirms the overall dominance both in speed and direction of winds with a NW (Shamal) component. Such winds tend to originate over the Saudi Arabian mainland (B.S.M.R.S., 1976).

The diurnal wind pattern has dominant WNW and N onshore directions, but in the morning (0700) the W and NW frequencies are more important than the north, while in the afternoon the north is much more frequent than the NW, and the west tends to be less frequent. The mean wind speed increases from 16.7Km/hr. in the morning, to 22.2Km/hr. in the afternoon (Persian Gulf Pilot, 1955, p.35).

The effect of the wind is important, as it plays both a direct and indirect role in sediment transport and denudation; directly while blowing over the land and indirectly as it also blows across the sea surface creating waves, whose size and direction are controlled by the direction, strength and fetch of the wind. The direction of wave approach is important in modifying the morphology of the coast and dune ridges, as their orientation is a response to the previous wind and wave approach. The major role of waves is to put sediments in suspension so

that they may be transported by littoral currents. In shallow nearshore areas, littoral currents have two major components, these are wind currents and the longshore component of oblique wave action. Both these components owe their energy and direction to the wind, thus the overall balance of wind and wave produces a slight longshore drift which is accompanied with physiographic developments.

Sudden storms caused by the Shamal have been recorded in January and February (Persian Gulf Pilot, 1955). These sudden unpredictable storms may cause extensive flooding on low areas especially if they coincide with extreme high tides.

Air circulation plays an important role in the process of evaporation and is of obvious significance in regions of chemically precipitated sediments.

#### 2.1.4 Humidity, Dew and Fog:

The high sea water temperatures of the Gulf, and the development of temperature inversions, results in high humidity levels.

In Bahrain, the mean daily maximum relative humidity is approximately 85% throughout the year, while the mean daily minimum relative humidity is higher in the winter (being approximately 50% from November to March), than in the summer (dropping to approximately 40 - 45% from April to October, see Fig.2.1 and Table 2.1). In the morning, the relative humidity is always higher than in the afternoon (Persian Gulf Pilot, 1955).

Fog is fairly common in Bahrain, and the mean number of days per month with fog or thick haze is 0.7 days in October, reaching 1.7 days in January and dropping to 0.5 days in March. From April to September it is generally low, the maximum being 0.2 days (Table 2.1).

Radiational cooling during the night leads to dew and water condensation onto objects near the ground. Frost occurs when the temperatures are below the freezing point. In Bahrain dew is common, but frost is nearly always absent as temperatures do not normally drop below the freezing point.

High humidity, fog and dew provide a fairly constant source of water

for flora, and supply water to the sabkha, and dissolve surface salts.

#### 2.1.5 Evaporation:

World wide, net evaporation is balanced by precipitation and runoff. The factors influencing this balance are latitude, altitude, winds, oceanic currents, vegetation, salinity and the distance from the sea (Bonython, 1966; Borchert and Muir, 1964).

In the Arabian Gulf, evaporation rates are generally high, and the mean annual evaporation rate for the whole of the Gulf is 1,440mm. (Privett, 1959) the evaporation rate being higher in summer than in winter.

In Bahrain, precipitation and runoff are small, and hence it is an area of net loss by evaporation. In Budayyi (an oasis in Bahrain), Wright and Ayub (1975) indicate that the amount of potential evapotranspiration varies from approximately 77mm. in January to 250mm. in June, but as Budayyi is an oasis and because of the moisture conditions beneath the trees, evaporation figures from Budayyi are 15 - 30% lower than those of other areas in Bahrain.

#### 2.1.6 Tides:

Tidal ranges are small, and even the largest tides in the Gulfs of Bahrain and Salwa seldom exceed 0.9m. (Sugden, 1963) due to the restriction of water movement by the numerous banks and shoals surrounding Bahrain (Fig.2.2). When the high tide is accompanied by a strong wind, flooding of the low areas may occur.

### 2.2 Geomorphology:

In the southwest sabkha, six geomorphic units have been identified (see Fig.2.2). These are:

- |                   |             |                                  |
|-------------------|-------------|----------------------------------|
| 1. Ridges         | 2. Sabkha   | 3. Salt Pan                      |
| 4. Accretion Zone | 5. Platform | 6. Aeolian sands with dune form. |

#### 2.2.1 Ridges:

From Az Zallaq* to Ras Dubas the shoreline is composed of a beach

* For localities and local names always refer to Fig.2.2.

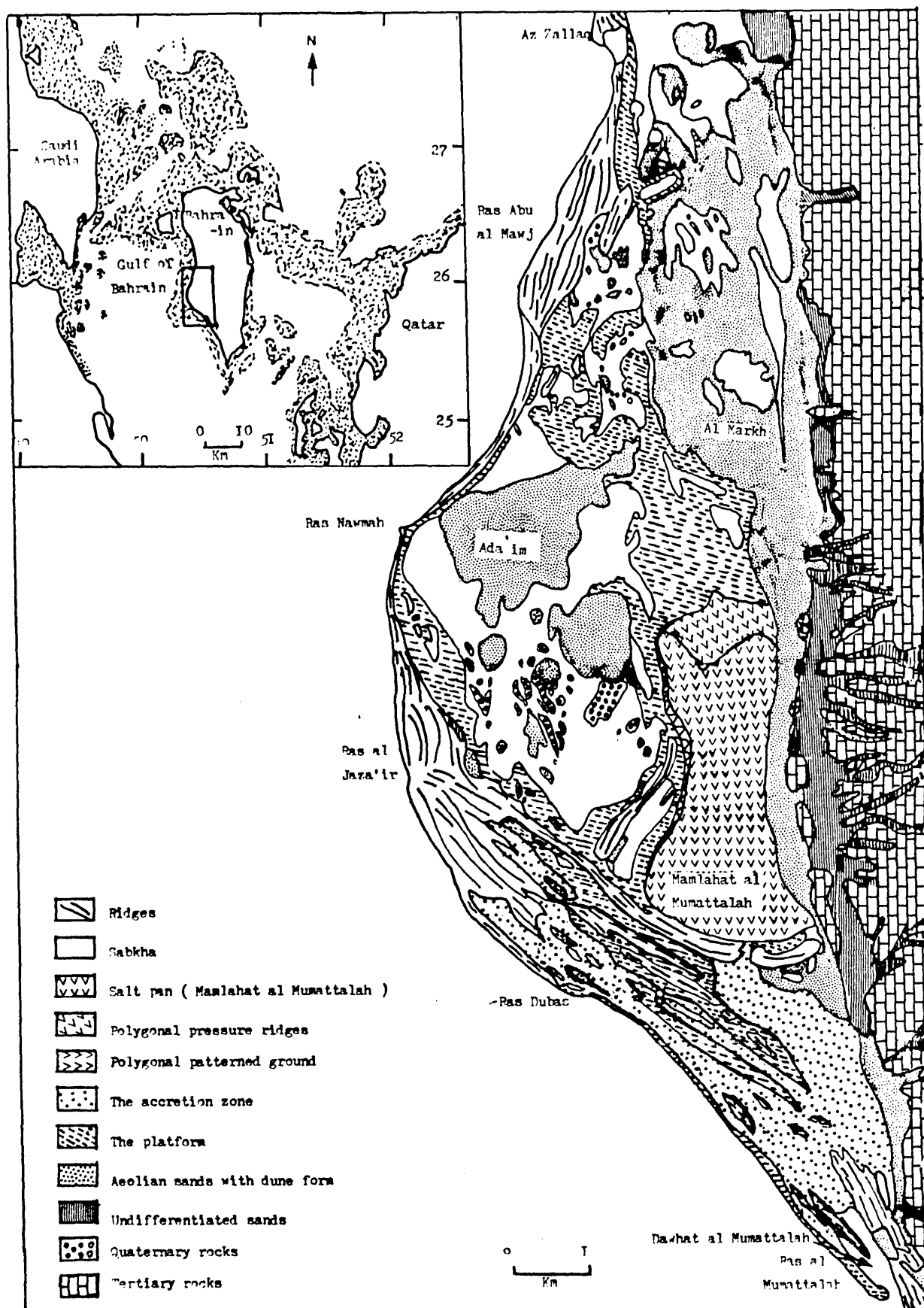


Fig. 2.2 The location of the area of study (box in map at top left) and the distribution of the geomorphic units.

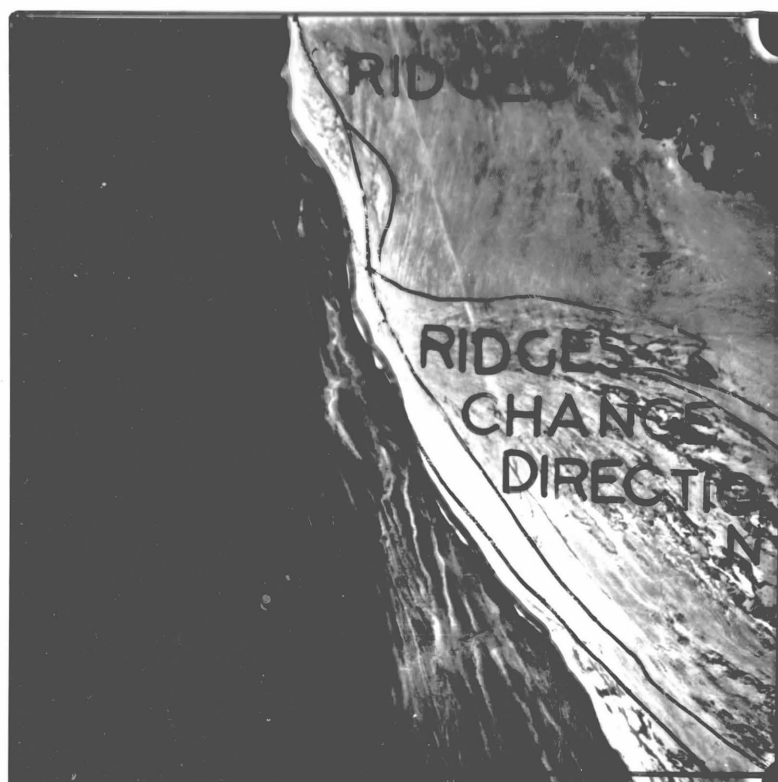


Fig. 2.3 Beach ridges, easily identified from air photographs.  
Southwest sabkha, Bahrain.

ridge complex (of Evans et al, 1969) with a narrow sandy beach (Fig. 2.2). The ridges have a flattened, wind scoured surface and are not obvious on the ground, but they are easily identified from air photographs (Fig.2.3). Coastal dunes are generally absent apart from one or two localities, but scattered nebkhas are not uncommon.

The complex widens gradually from 250m. wide south of Az Zallaq to about 750m. wide east of Ras Abu al Mawj and it then becomes narrower (often less than 100m. wide) and lower towards Ras Nawmah. From there to Ra's al Jazair the complex widens to more than 1Km. and rises to about 3.2 - 3.6m., its innermost parts having a flattened crest at approximately 4m. From Az Zallaq to Ras al Jazair, low cliffs cut in cemented shelly beach ridge material are almost continuous, and are fronted by a beach and beach rock mantled low tide terrace. South of Ras al Jazair, the beach ridge complex swings to the southeast diverging and becoming lower (2.5m. maximum elevation). Here in the more sheltered parts the ridges are no longer closely packed together, but become separated by sand flats with a typical sabkha surface and the complex gradually loses its definition and grades into a low accretionary plain towards Ras al Mumattalah. South of Ra's Dubas, there are only sandy beaches, giving way inland to flat areas.

Southeast of Ra's al Jazair, a curving branch of the same complex extends inland with a southeast trend to cut across the southern end of Mamlahat al Mumattalah (the salt pan). Towards the end of the branch there is an area where the ridges are absent, and this may be the site of an old inlet. The maximum height in this curving branch is 3.2m.

West of the salt pan, there are ridges having a NE - SW trend and a maximum height of 2.8m. Their crests are generally flattened (Fig.3.91).

#### 2.2.2 Sabkha:

This flat plain varies in elevation from just above A.H.W.M. to 0.6m. below it. It is generally surrounded by a slightly higher platform (see section 2.2.5, Fig.2.2), but towards the east the dunefields of Hawrat Inqa and Al Markh form its borders. Around Adaim it is mantled by isolated large dunes and dune fields (Fig.2.2), and in the centre of the sabkha white Quaternary limestones outcrop at nearly the same level as the surrounding surface sands (Fig.2.4) or as a sediment veneered pavement, but occasionally these limestone form small mesas (0.5-1m.) above the surrounding levels. There are also linear or arcuate upstanding remnants of cemented cerithid-rich shelly ridges which are



Fig. 2.4 Planated Quaternary limestones cropping out at nearly the same level as the surrounding sabkha sediments.



Fig. 2.5 Sabkha surface after flooding.

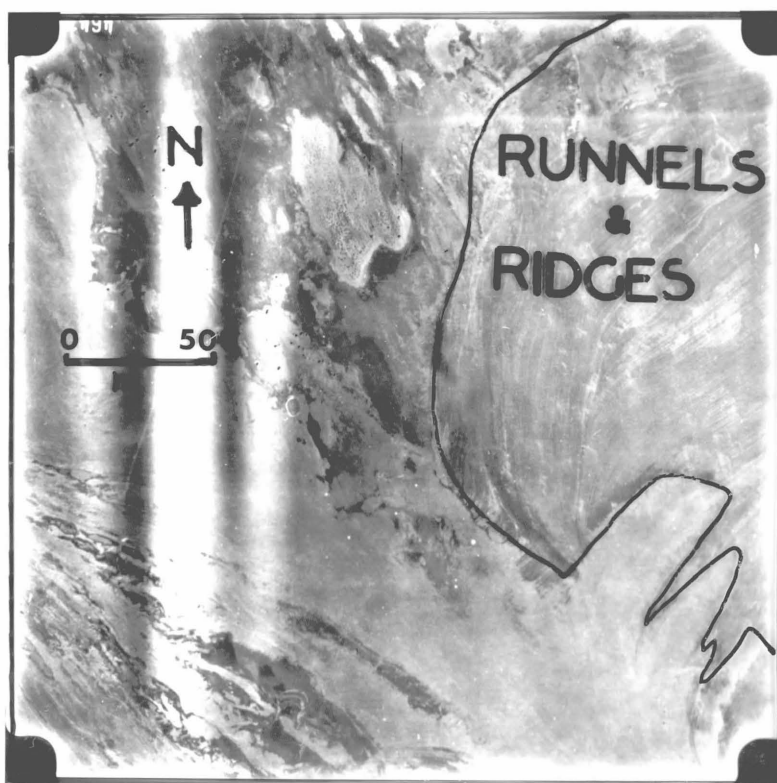


Fig. 2.6 Linear alternations of shallow runnels and ridges,  
Southwest sabkha, Bahrain. (Air photograph).

sometimes as much as 1m, above the surface.

Most of the sabkha's surface is encrusted and blistered by salt concentrations, but in some localities the blistered surface has smoothly arcuate or occasionally linear alternations of shallow runnels and ridges (Fig.2.6), with amplitudes of a few 10s of mm. and wave length of approximately 1m.

When the sabkha is flooded, it has a relatively smooth surface, and is a pale brown colour (Fig.2.5).

The general morphology of the sabkha together with its detailed relief forms and features indicate that it has experienced severe deflation (B.S.M.R.S., 1976).

#### 2.2.3 Salt Pan (Mamlahat al Mumattalah):

The salt pan (Fig.2.2) is defined to the west and south by higher ridges, and to the east by a narrow strip of low dunes and nebkhas fringing the dipslope. The surface elevation of the pan is entirely below A.H.W.M., its lowest part being approximately 1m. below this level. It stretches over 5Km. from north to south, and 2Km. from east to west. The surface is very flat and when dry is blistered and cemented with salt to form a typical sabkha surface. When wet after rainstorms and flooding, the surface becomes smooth and the salts dissolve. Around its margins there are superficial traces of temporary and rapidly receding flood levels formed mainly after rainstorms which create an ephemeral lake in this flat enclosed pan. This lake is soon reduced and removed by evaporation and infiltration, leaving a thin film of halite crystals especially towards the lower southern side.

On the northern side of the pan there is a wide zone of polygonal pressure ridges of gypsum (Fig.2.7). A narrower zone of these polygons lines the western edge of the pan, while they occur discontinuously on its eastern side.

#### 2.2.4 The Accretion Zone:

This accretion zone lies to the south of the area of study, and extends from the nebkha zone at the base of the backslope almost to the coast, and grades south into the intertidal flats around Dawhat al

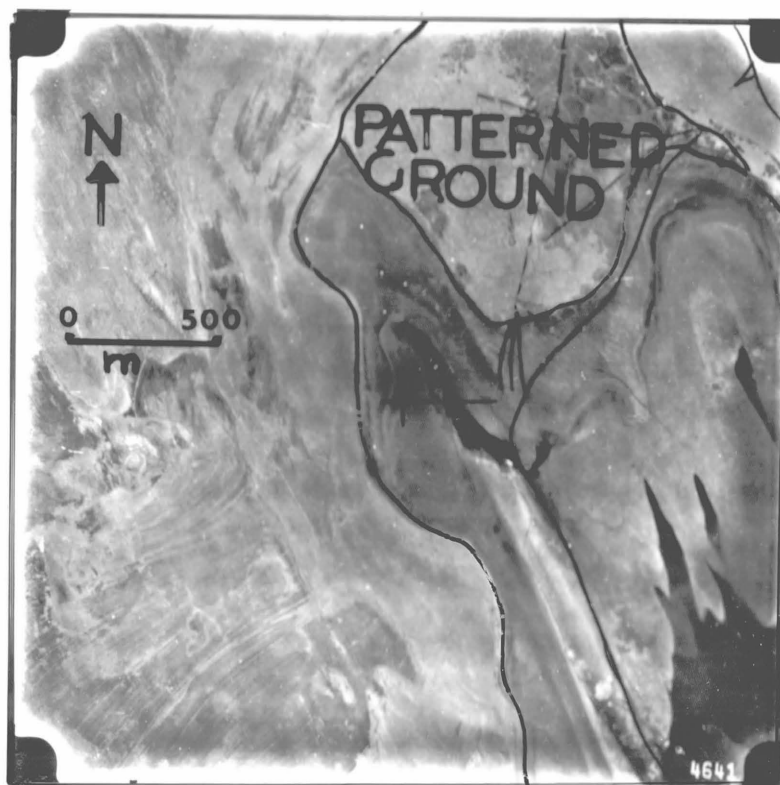


Fig. 2.7 Zone of polygonal pressure ridges of gypsum.  
Mamlahat al Mumattalah, southwest sabkha, Bahrain.

Mumattalah (Fig.2.2). Dawhat al Mumattalah is sheltered from the north-west and west by sandspits, and shows poorly developed algal mats. The accretion zone is lower than the platform and in areas is interfingered with it. This southern area is generally flat and has a maximum elevation of 2.4m., the adjacent beach ridges and the coastal strip being slightly higher.

#### 2.2.5 The Platform:

The platform surrounds the sabkha (Fig.2.2) and their junction takes the form of a low scarp approximately 0.6m. high. The platform forms the northern and western margin of the salt pan, and extends to the nebkhas at the backslope and the dunefields of Al Markh.

It forms an almost horizontal featureless expanse, variably mantled with layers of fine cerithid-rich shelly gravel. The gravels are commonly cemented, and these cemented zones often show polygonal joint patterns. It has an elevation of 2.3 - 2.7m., and shows no traces of former beach ridge alignments.

The platform has been extensively deflated, and in many places "windows" reveal the underlying sands in shallow hollows, some 0.6m. deep.

#### 2.2.6 Aeolian Sands with Dune Form:

Strips and patches of low dunes (dunes deflated by the wind into patterns with a NW - SE orientation) and nebkhas are common in many parts of the area of study, but large and high dunes and dune fields are restricted to its northern and central parts.

The dune fields of Hawrat Inqa and Al Markh form the northern margin of the area, and cover an area of  $6\text{Km}^2$ . The dunes reach heights of 5.5m., and form the most distinctive topographic features of the area. The central parts of these dune fields are characterised by complexes of parabolic dunes (Fig.2.8), aligned NW - SE, with gentle NW slope and steeper slip faces to the SE, there are signs of severe deflation in this area. These parabolic dunes grade outwards into a zone of lower mounded dunes. Smaller dune fields do not have these parabolic dunes, but show irregular hummocky topography with sand tails.

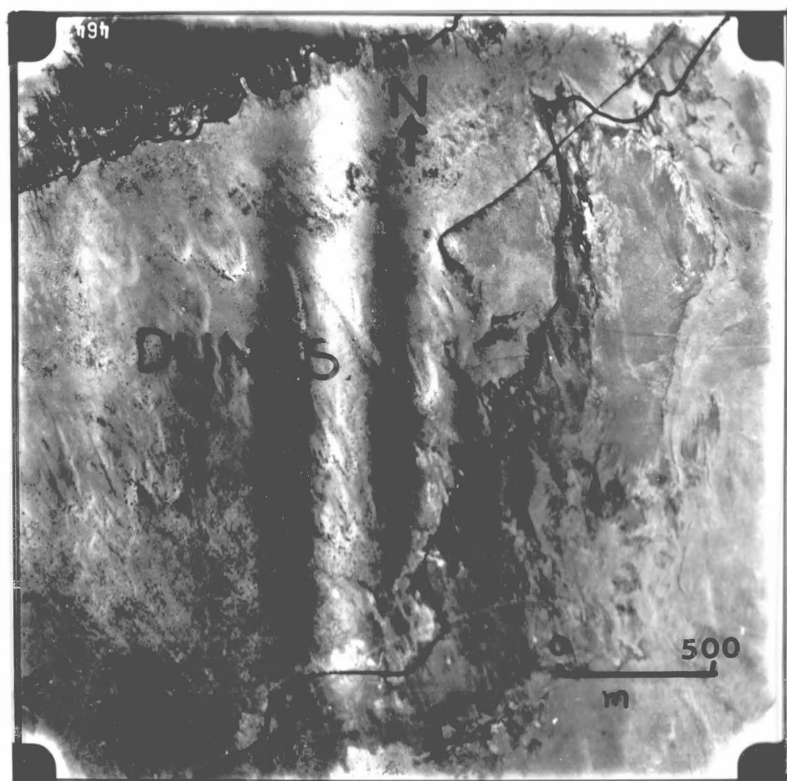


Fig. 2.8 Parabolic dunes, southwest sabkha, Bahrain.  
(Air photograph).

Smaller isolated dunes commonly occur in lines having a NW - SE orientation and rise 3 - 4m. above the general surface. They appear to represent the deflated remnants of formerly more extensive dune fields (B.S.M.R.S., 1976), and often show SW inclined cross bedding.

In the central part of the southwest sabkha, all the dunes have sharply defined boundaries against the sabkha and platform areas, while in the Hawrat Inqa and Al Markh fields their limits are less distinct.

The dune areas have a sparse cover of vegetation, mainly tamarisk particularly on their crests and windward NW slopes. A deep archaeological excavation near Adaim reached the water table, and the water was drinkable, and may be the source of water for the vegetation.

## CHAPTER THREE

### Sediment Distribution and Description

### 3. Introduction:

The maximum thickness of the unconsolidated Recent sediments beneath the southwest sabkha is unknown as their base was not reached (this thickness is probably not great, and shallow drilling is required to confirm this).

The author has identified four main units from the sediments sampled, and these are overlain by a thin veneer of surface sediments. Each geomorphic unit as described in Chapter Two has a characteristic type of surface sediment. The four units are: Unit 1, Unit 2, Unit 3 and Unit 4. Units 3 and 4 are sub-divided into Sub-units (Fig.3.91). Apart from those four units, the author has identified different units forming the dunes and other units forming the salt pan. The sediments of these units were formed under different environments of deposition to those of the four units and will be discussed separately. For the location of the profiles and pits see Fig.3.89, for the positions of the samples in each pit see Fig.3.90, for the sample numbers see Table 3.1, and for the distribution of the sedimentary units see Fig.3.91.

The distinction between the units is based on the colour and sedimentary structures of the sediments in the unit as a whole, and the size and type of the grains making up the sediments.

In this chapter the lithology and distribution of the sediments forming the units are described, followed by a description of the surface sediments on the previously described geomorphic units, the sediments of the dunes and the sediments of the salt pan. The description will deal with the sedimentary structure, texture, grain constituents and mineralogical composition of the sediments, based on the pit descriptions, field photographs and the laboratory studies. The chemical composition of the sediments and groundwaters will be dealt with in Chapter Four.

The Munsell Colour Chart is used to describe colours, and for grain size both Wentworth's and Krumbein's classifications are used.

The percentages of the mineralogical compositions for both the sand and the silt plus clay grade material are plotted and contoured (see Figs.3.92 to 3.102 at the end of this chapter and Appendix 1).

The contour intervals are shown at the bottom of each figure. In some cases specific contours have been used to prevent clustering of contour lines and make understanding easier. The grain size statistical parameters are tabulated in Appendix 2.

In the following sections, the description of the grain types is for the sand grade material alone, the sedimentary structures and mineralogy etc., are for the whole sediment.

### 3.1 Unit 1:

The sediments of Unit 1 are mainly light brownish grey, moderately well sorted, medium calcareous quartz arenites. This unit was reached in some pits in profiles I - II and VI - VII (Fig.3.91), but its thickness is unknown, as the base of the unit was not reached.

The sediments of this unit are loose, homogeneous and have a percentage of silt plus clay grade material ranging from 0.0 to 10.0% (Fig.3.102).

The sand grade material of Unit 1 consists of quartz, carbonate, magnetite and other heavy mineral grains. The quartz grains are generally of medium sand grade, with a few coarse sand grade grains, subangular to subrounded, subspherical, frosted and with abundant polycrystalline grains (Fig.3.1). The fine sand grade quartz grains generally have a vitreous lustre (Fig.3.1).

The carbonate grains consist of molluscan skeletal fragments, foraminiferal tests and altered grains (similar to those described by Houbolt, 1957; Purdy, 1963; and Kendall and Skipwith, 1969) which are virtually indistinguishable from each other (Fig.3.2) and in the rest of this account, these grains will be described as peloids (according to Bathurst, 1971, this useful term, peloid, allows reference to grains composed of micrite or microspar without the need to imply any particular mode of formation). Generally it is not possible to define the origin of these grains, but in some instances the external shape may be an indication of the grain's origin (similar to Kendall and Skipwith, 1969). The carbonate grains are generally of medium sand grade, apart from those in profile I - II which are of coarse sand grade. In profile VII - VIII carbonate grains are generally scarce in the sand grade, and are mainly peloids (Fig.3.1) but in profile I - II, carbonate grains are common and have the following characteristics: the Molluscan

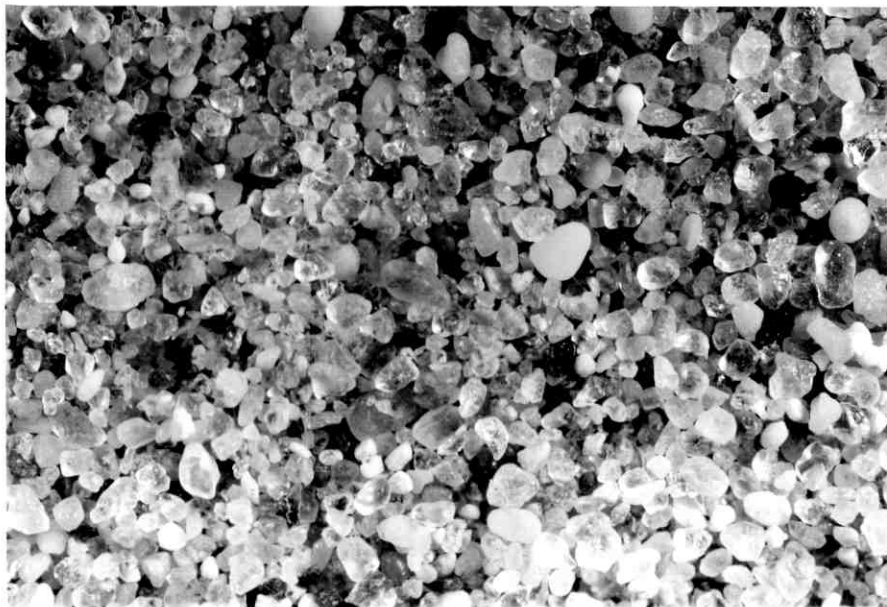


Fig. 3.1 Medium calcareous quartz arenite of Unit 1, sample 282, pit 13/61. Note carbonate grains are scarce. Loose grains. X25.

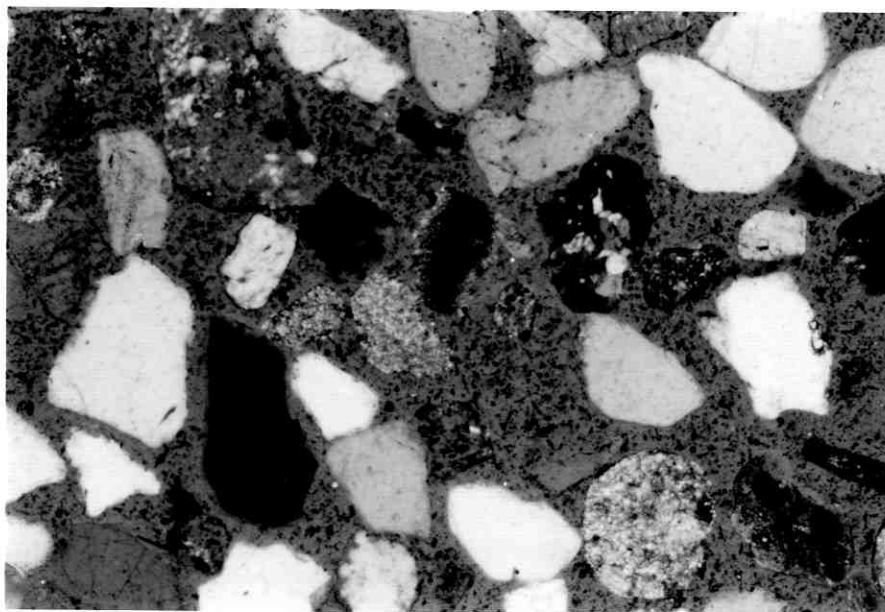


Fig. 3.2 Medium calcareous quartz arenite of Unit 1, sample 282, pit 13/61. Note alteration of carbonate grains. Impregnated grains. Crossed nicols. X90.

skeletal fragments still retain their original colour and shape, while the foraminiferal tests show stages of alteration from porcellaneous to a milky white colour under reflected light while retaining their external shape. The peloids all have a milky white colour under reflected light. There are also a few straight and coiled calcareous worm tubes.

Magnetite, blue and green amphiboles and other heavy minerals are present in the fine sand fraction.

Mineralogically the sediments of Unit 1 consist of quartz, carbonate minerals and feldspars, having the following ranges of percentages (Figs 3.92 - 3.101): quartz (60 - 90%), carbonate minerals (5 - 36%); aragonite (0 - 25%), calcite (3 - 12%), dolomite (1.5 - 2.5%), and high-magnesium calcite (0 - 2%) and feldspars (1.5 - 4.5%).

The higher percentages of silt plus clay, and carbonate minerals are found towards the north at profile I - II, while at profile VII - VIII, silt plus clay values are very low, and the percentages of carbonate minerals are also low with aragonite absent.

### 3.2 Unit 2:

The sediments of Unit 2 are mainly yellowish orange, moderately well sorted, fine to medium calcareous quartz arenites. The thickness of this unit is variable, ranging from 0.25 to 1.0m. This unit occurs in pits in profiles I - II, VII - VIII (Fig.3.91) and in some of the scattered pits in the sabkha.

At profile I - II and in some of the scattered pits in the sabkha, the sediments of this unit are loose and homogenous, but in parts of the sabkha some of the sediments are cemented with gypsum. In the second pit of profile VII - VIII, pit 13/39, the sediments are layered; sandy layers interbedded with silty layers (Fig.3.3). The following pits of this profile are those dug in the sabkha, the surface of which is characterised by alternations of runnels and ridges, their sediments are loose and laminated, the dip of the laminae increases further down the profile (Figs.3.5 and 3.8). At pit 13/43, the sediments show slumping (Fig.3.6) and according to Bigarella, 1972, slumping may occur under wet or dry conditions. Gypsum nodules were recorded in the field descriptions, but none were found in the material returned for analysis.



Fig. 3.3 Sandy layers interbedded with silty layers, Pit 13/39.

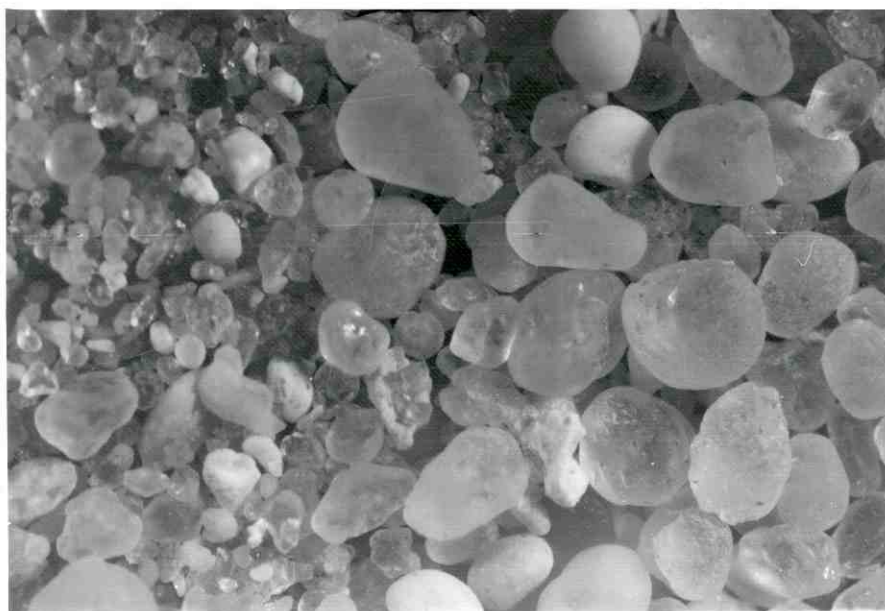


Fig. 3.4 Calcareous quartz arenite. Sample 362, pit 13/39. Note two types of quartz; coarse sand grade rounded and frosted and fine to medium sand grade grains. Loose grains. X25.



Fig. 3.5 Pit 13/40. Note , dipping of beds (compare with Fig. 3.8 further down the profile).



Fig. 3.6 Slumping of sediments, pit 13/43. Note laminations at the top right side of the pit.



Fig. 3.7 Fine to medium quartz arenite. Sample 355, pit 13/43. Loose grains. X25.

The percentage of silt plus clay grade material ranges from 0.0 to 5.5% (Fig.3.102).

The sand grade material of Unit 2 consists of quartz, carbonate, magnetite and other heavy mineral grains. The quartz grains are mainly fine to medium sand grade, but towards and in profile I - II, particularly towards the sea, the grains tend to be coarser and are sometimes of very coarse sand grade (Figs.3.4 and 3.10). The coarse and medium sand grade grains tend to be rounded, subspherical and frosted to polished, while the fine sand grade quartz grains are vitreous, subangular and sub-rounded (Figs.3.7, 3.9 and 3.11).

The carbonate grains are mainly altered, milky white peloids of sand grade size (Figs.3.9 and 3.11). Towards the edges of the sabkha, there are some Molluscan fragments which are coarse and have a milky white colour in reflected light, together with altered foraminiferal tests which still retain their original shape.

Magnetite, blue and green amphiboles and other heavy minerals are present in the fine sand grade fraction.

Mineralogically the sediments of Unit 2 consist of quartz, carbonate minerals and feldspars having the following ranges of percentages (Figs. 3.92 - 3.101); quartz (70 - 92%), carbonate minerals (5 - 20%); calcite (3 - 15%), dolomite (2 - 5%) and high-magnesium calcite (0 - 2.5%), and feldspars (2 - 7%). At pit 13/3, the sediments of Unit 2 also have celestite which increases with depth from 2% to 12.2% (see Fig.3.101).

The higher percentages of calcite and feldspars are found towards profile I - II.

### 3.3 Unit 3:

Unit 3 is composed of two sub-units, 3a and 3b, having different origins.

#### 3.3.1 Sub-unit 3a:

The sediments of this sub-unit are mainly pinky-yellowish gray, poorly sorted, bimodal (gravel grade to coarse sand and medium to fine sand) quartzose skeletal calcarenites. This sub-unit was only reached in pits 11/28 and 13/1 in profile I - II, and in pits 15/26 and 15/31



Fig. 3.8 Pit 13/60. The sediments are loose and laminated. Note high angle of dip.



Fig. 3.9 Calcareous quartz arenite. Sample 352, pit 13/60. Note alteration of carbonate grains (peloids). Loose grains, X25.

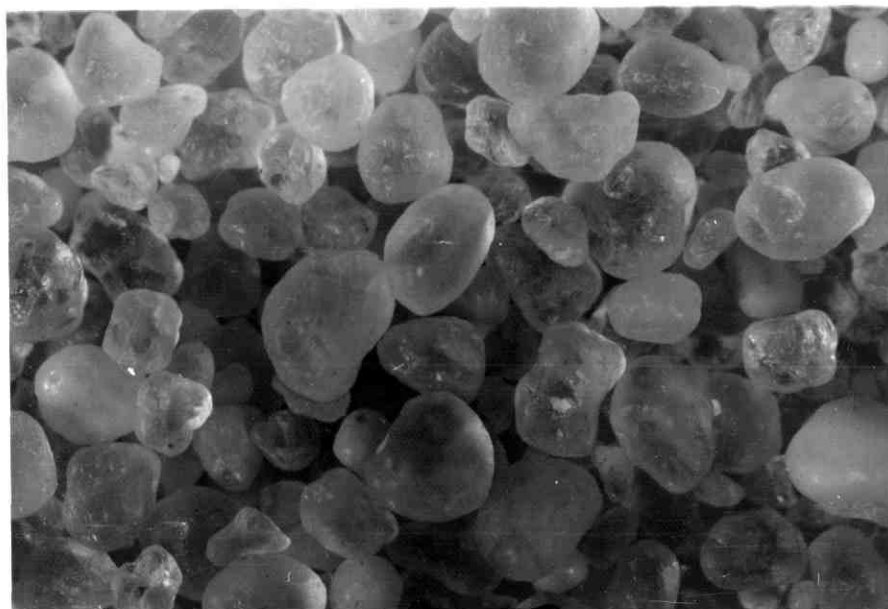


Fig. 3.10 Quartz arenite, sample 1123, pit 13/38. Two types of quartz; very coarse sand grade. Loose grains, X25.



Fig. 3.11 Calcareous quartz arenite. Sample 353, pit, 13/59. Note peloids (milky white colour). Loose grains, X25.

in profile IX - X (Fig.3.91), and its thickness varies from 0.4 - 0.6m.

The sediments are generally loose and homogenous, but in the pits at profile I - II the top 50 - 100mm. of the sediments are strongly cemented, in some cases by acicular aragonite sement. Algal peat occurs in some of the pits in the seaward part of profile IX - X. The percentage of the silt plus clay grade material ranges from 1.0 to 7% in the pits at profile I - II, while it reaches up to 46% in the sediments of the pits at profile IX - X (Fig.3.102).

The sand grade material of the sub-unit consists of carbonate and quartz grains and a very small amount of heavy minerals. The carbonate grains are mainly medium to fine sand grade peloids (Figs. 3.12 and 3.13) and alteration of the carbonate grains is extreme at profile IX - X (Fig.3.13). Next in abundance are whole bivalve shells, foraminiferal tests and gastropod shells, and skeletal fragments.

The skeletal grains are generally gravel grade to very coarse sand grade, and still retain their original colours. Some foraminiferal tests are however in different stages of alteration from porcellaneous to milky white. Skeletal grains are not as common in the sediments of profile IX - X as in those of profile I - II.

The quartz grains are coarse to medium sand grade, rounded to sub-rounded, subspherical and are frosted. Some of the finer sand grade quartz grains are vitreous and subangular. Magnetite and other heavy minerals are present in small amounts.

Mineralogically, the sediments of Unit 3a consist of carbonate minerals, quartz and feldspars (Figs.3.92 - 3.101); carbonate minerals (60 - 84%); aragonite (48 - 65%), high-magnesium calcite (3 - 10%), calcite (4 - 7%) and dolomite (2 - 4%), quartz (13 - 27%) and feldspars (1.3 - 5.9%).

### 3.3.2 Sub-unit 3b:

The sediments of this sub-unit are mainly light grayish orange, poorly sorted, bimodal (gravel grade and coarse to medium sand grade), calcareous skeletal quartz arenites. This sub-unit was exposed in some pits in profiles III - IV, V - VI and IX - X (Fig.3.91) but its thickness was undetermined, since the base of this sub-unit was not reached.

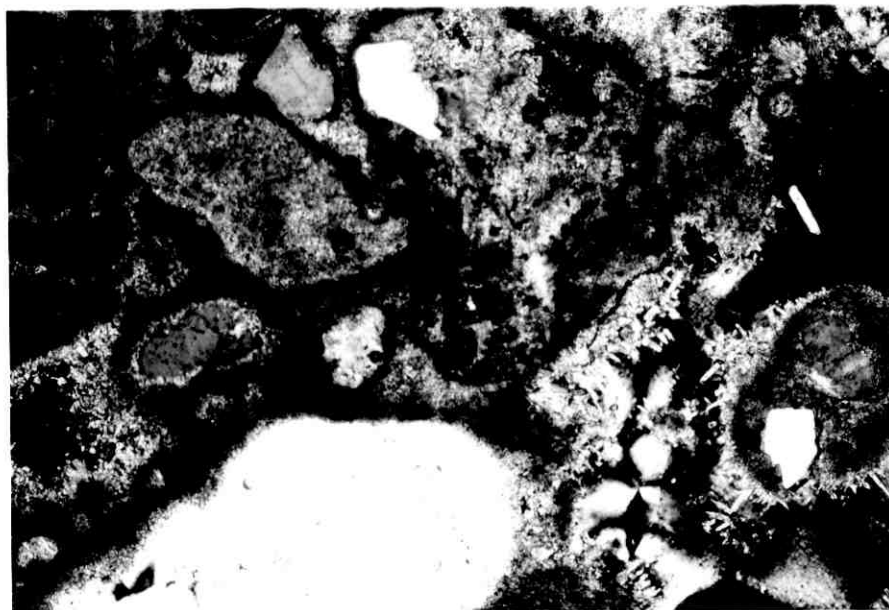


Fig. 3.12 Cemented skeletal calcarenite. Sample 1091, pit 11/28.  
Note alteration of carbonate grains. Crossed nicols.  
X90.

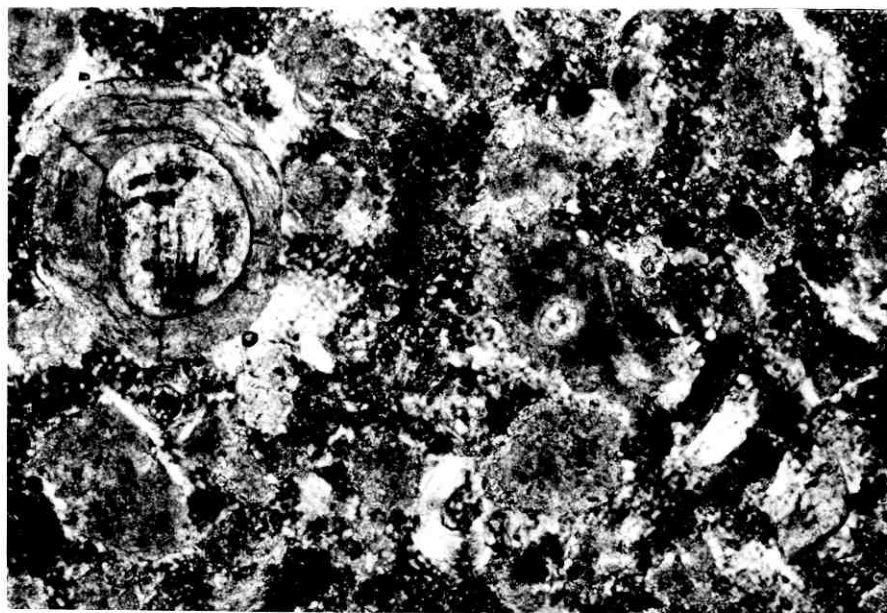


Fig. 3.13 Calcarenite. Sample 17/044, pit 15/26. Note alteration  
of carbonate grains. Crossed nicols. X90.

The sediments are mainly loose and layered, but in the pits at profile III - IV, they are compact to weakly cemented and layered. In pit 15/5, the sediments are loose but with cemented layers up to 50mm. thick with lenses of whole shells and pellets. Cementation appears to increase with depth (B.S.M.R.S., 1976), the grains have a uniform fringe of fibrous aragonite cement (Fig. 3.14). The silt plus clay fraction is generally less than 1%, but a few samples have higher values up to 6.5% (Fig. 3.102).

The sand grade material mainly consists of quartz and carbonate grains, with very small amounts of magnetite, blue and green amphiboles and other heavy mineral grains (Figs. 3.15 and 3.16). The quartz grains are of two types; mainly medium sand grade quartz grains which are subrounded to subangular, and common very coarse sand grade to coarse sand grade quartz grains which are well rounded and spherical. Towards the sea, quartz grains generally have a thick carbonate coating, which becomes thinner further inland and is absent still further inland.

The carbonate grains are composed mainly of coarse sand grade, with some gravel grade, Molluscan fragments and whole shells which still retain their original colour and texture. Alteration of the carbonate grains is however common, especially in the pits which are cemented (Fig. 3.14), the grains have a milky white colour under reflected light and their origin is not known. The altered grains are generally of a medium sand grade size.

Magnetite, blue and green amphiboles, and other heavy mineral grains are in very small amounts, and are of very fine sand grade.

Mineralogically the sediments consist of quartz, carbonate minerals, feldspars and celestite having the following ranges (Figs. 3.92 - 3.101); quartz (50 - 80%), carbonate minerals (18 - 40%), aragonite (9 - 32%), calcite (3.5 - 14%), high-magnesium calcite (0 - 2%) and dolomite (0.5 - 2%), feldspars (1.5 - 6%) and celestite (1 - 3.5%). In the sediments of profile III - IV towards the sea aragonite is common and calcite is only present in small amounts, while further inland the amount of aragonite decreases and calcite increases. Celestite is only present in the sediments of the pits at profile IX - X while gypsum is present in minor amounts (less than 1%) in the sediments of the pits at profile III - IV.

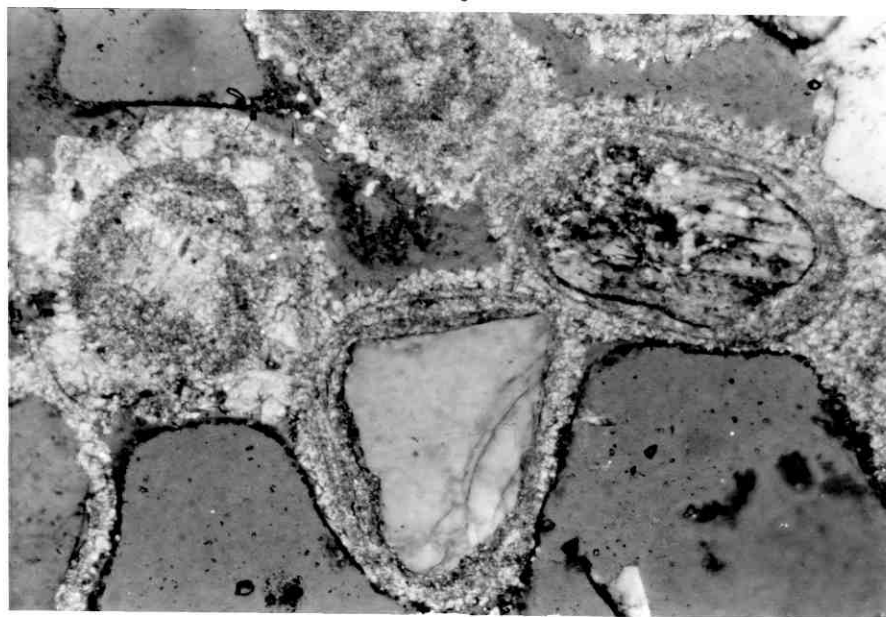


Fig. 3.14 Uniform fringe of fibrous aragonite cement. Sample 1150, pit 13/34. Note cement fringing micritized carbonate grains and quartz grain. Crossed nicols. X144.



Fig. 3.15 Calcareous skeletal quartz arenite. Sample 484, pit 15/16.  
Note alteration of carbonate grains. Loose grains. X25.



Fig. 3.16 Calcareous skeletal quartz arenite. Sample 1153, pit 13/35  
Loose grains. X25.

### 3.4 Unit 4:

Unit 4 is composed of four sub-units: 4a, 4b, 4c and 4d.

#### 3.4.1 Sub-unit 4a:

The sediments of this sub-unit are mainly very pale orange, moderately to poorly sorted, medium to fine, slightly quartzose skeletal pelletal calc arenite. This sub-unit was exposed in some pits (e.g, pit 15/22, Fig. 3.17), in profiles I - II, V - VI, and IX - X (Fig. 3.91) its thickness varies from 0,1m. to 0,25m., being thicker in the pits of profile I - II.

The sediments of this sub-unit are mainly loose and homogenous apart from its occurrence in pit 15/6, where the sediments at the bottom of the unit are strongly cemented. The percentage of silt plus clay grade material ranges from 5 to 36% (Fig. 3.102).

The sand grade material consists of carbonate and quartz grains. The carbonate grains are mainly pellets, those in the north are of a medium to fine sand grade and tend to be altered, lose shape and become smaller in size (Fig. 3.18), while those in the pits in the south are a coarse to medium sand grade. There are also a few cerithid gastropod and bivalve skeletal fragments of coarse to very coarse sand grade, some of which are altered and have a milky white colour under reflected light.

The quartz grains are generally in minor amounts apart from pit 15/6, where they are common. Quartz grains are of coarse to medium sand grade, subangular, subspherical and some grains are frosted. Heavy minerals are present in very small amounts.

Mineralogically the sediments consist of carbonate minerals, quartz and feldspars, having the following ranges (Figs. 3.92 - 3.101): carbonate minerals (75 - 95%); (aragonite (65 - 86%), calcite (5 - 8%), dolomite (2 - 5%) and high-magnesium calcite (0 - 2%)), quartz (4 - 20%) and feldspars (1 - 1.5%). In pit 15/6, the sediments have a higher percentage of quartz (40%), a lower percentage of carbonate minerals (55%) and celestite is present making up approximately 5% of the sediments.

#### 3.4.2 Sub-unit 4b:

The sediments of Sub-unit 4b are mainly pale grayish orange,



Fig. 3.17 Sediments of Sub-unit 4a, skeletal pelletal arenite (cream colour bottom of pit), pit 15/22.

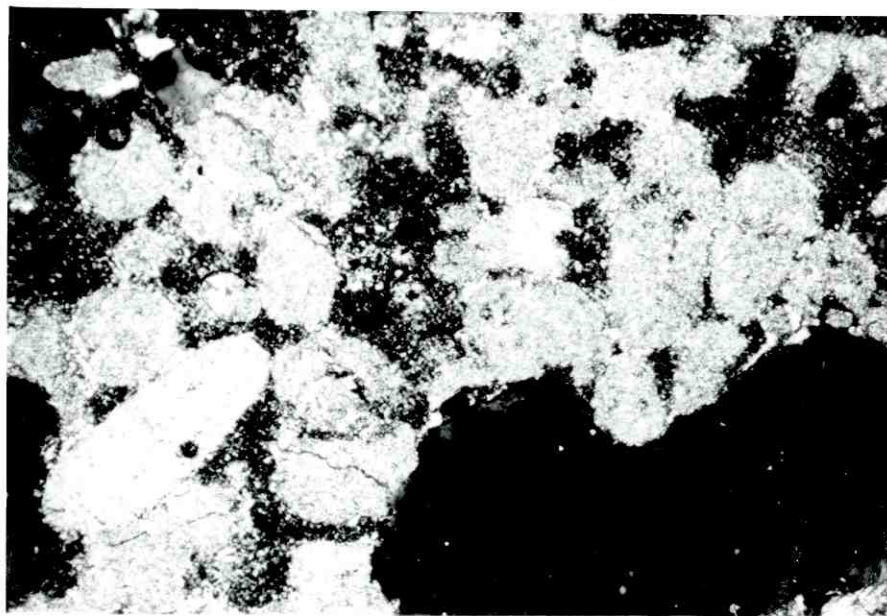


Fig. 3.18 Pelletal arenite. Sample 1084, pit 11/27. Note altered pellets. Impregnated grains. Crossed nicols. X40.

moderately to poorly sorted, slightly gravelly to coarse skeletal calcareous quartz arenites. This unit has been encountered in profiles I - II, III - IV, V - VI and IX - X (Fig. 3.91), having a minimum thickness of 0.6m.

The sediments of this sub-unit are generally loose and homogenous but at pit 13/33 the grains are cemented towards the bottom of the unit with an acicular aragonite cement (Fig. 3.23), and at pit 15/15 there are layers of gravel grade to coarse sand grade cerithid gastropods and skeletal fragments (Figs. 3.19, 3.20 and 3.21). Where it crops out at the surface it is generally covered with a shell lag. The percentage of silt plus clay grade material ranges from 0 - 7%, with very few sediments containing up to 1% silt and clay (Fig. 3.102).

The sand grade material consists of quartz, carbonate, blue and green amphiboles and other heavy minerals and opaque grains. The quartz grains are of two types, these are: mainly of medium sand grade, sub-angular, subrounded and frosted, (Fig. 3.20), the rest are very coarse sand grade grains, which are rounded, subspherical and frosted. Towards the sea some of the quartz grains have a thick carbonate coating (Fig. 3.22) but further inland the carbonate coating is absent.

The carbonate grains are generally gravel grade to coarse sand grade, and consists of whole bivalve and gastropod shells, and Molluscan fragments, some of which have their original colours and textures, and others show stages of alteration (Figs. 3.20, 3.21 and 3.22).

Coarse to medium sand grade black and bluish grains are present in small amounts, and occasional blue and green amphiboles and other heavy minerals are present in the finer sand fraction.

Mineralogically, the sediments are composed of quartz, carbonate minerals, feldspar and celestite, having the following percentages (Figs. 3.92 - 3.101): quartz (30 - 60%), carbonate minerals (25 - 66%); (aragonite (10 - 60%), calcite (3 - 16%), high-magnesium calcite (0 - 4.8%) and dolomite (1 - 3%)), feldspars (1 - 6.5%) and celestite (0 - 6.3%). Generally, the higher carbonate mineral content occurs when the unit crops out at the surface and is covered by a surface lag of shell-rich sediment e.g. pit 13/33.

Fig. 3.19 Skeletal rich layers interbedded with skeletal poor layers. Pit 15/15.



Fig. 3.20 Coarse skeletal quartz arenite of the skeletal poor layers of pit 15/15. Sample 397. Loose grains. X25.



Fig. 3.21 Quartzose skeletal arenite of the skeletal rich layers of pit 15/15. Sample 399. Loose grains. X25.





Fig. 3.22 The sediments of Sub-unit 4b, sample 1148, pit 13/33 towards the sea. Note abundant carbonate grains, quartz grains with a thick carbonate coating, grapestones, and altered carbonate grains. Loose grains. X25.

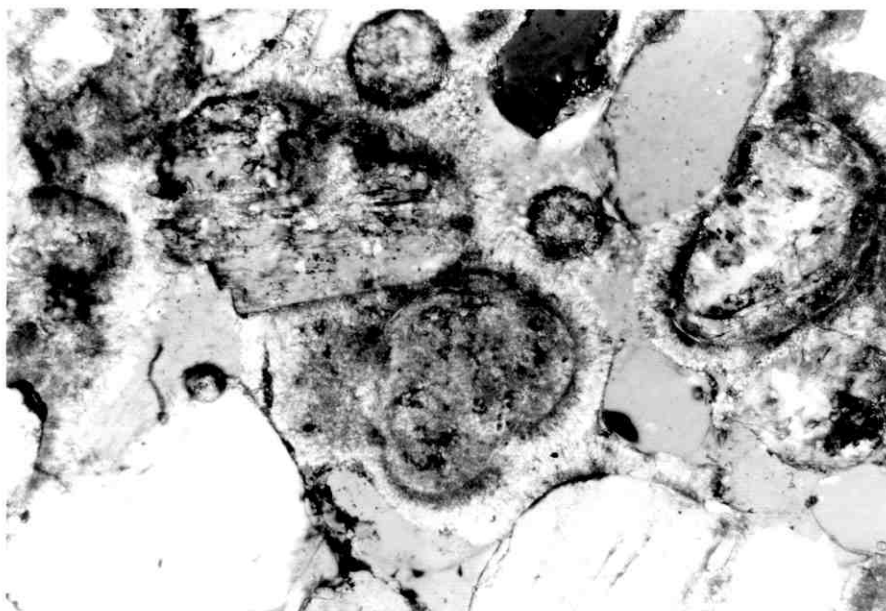


Fig. 3.23 Uniform fringe of fibrous aragonite cement. Sample 1148, pit 13/33. Impregnated rock. Crossed nicols. X144.

### 3.4.3 Sub-unit 4c:

The sediments of this sub-unit are dark yellowish orange, moderately sorted, coarse to medium skeletal calcareous quartz arenites. This unit has been encountered in pits in profiles V - VI and IX - X (Fig. 3.24) having a minimum thickness of 120mm., its maximum thickness is unknown since in many pits the base of this unit was not reached.

The sediments in this unit are loose and laminated (Fig. 3.24). The percentage of silt plus clay grade material is negligible apart from the sediments of pit 15/27 which have a silt plus clay grade percentage of approximately 15%.

The sand grade materials are mainly composed of quartz and carbonate grains (Fig. 3.25, 3.26, 3.27 and 3.28). The quartz grains are mainly medium sand with a few coarse sand grade quartz grains. The medium grains are mainly subrounded, subspherical and some are frosted, while the coarse grains are rounded, spherical and frosted.

Heavy minerals are present in the fine sand grade in small amounts.

The carbonate grains are mainly Molluscan skeletal fragments having their original colour and texture, but some grains are in stages of being altered. Occasional porcellaneous foraminiferal tests occur (Fig. 3.27), and in some pits peloids are also present.

Mineralogically, the sediments consists of quartz, carbonate minerals, feldspars and celestite having the following ranges of percentages (Figs 3.92 - 3.101): quartz (50 - 75%), carbonate minerals (12 - 38%); (aragonite (0 - 30%), calcite (3 - 10%), high-magnesium calcite (1 - 2.5%) and dolomite (1.5 - 2.5%)), feldspars (1 - 4.5%) and celestite (0 - 4%).

### 3.4.4 Sub-unit 4d:

The sediments of this sub-unit are light orangish gray, poorly sorted, calcilutitic quartzose calcarenites. The sediments of this unit have been encountered in profiles V - VI and IX - X having a thickness of 50 - 150mm.

The sediments are loose and homogenous. The percentage of silt plus clay grade material ranges from 30 to 50% (Fig. 3.102).

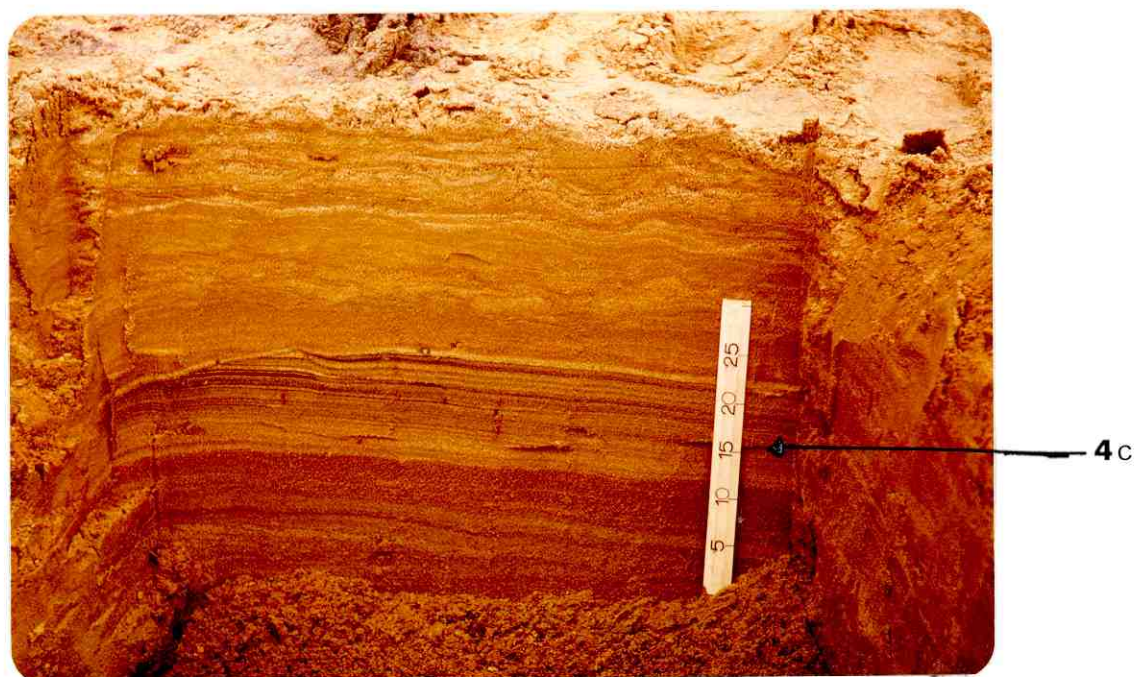


Fig. 3.24 Pit 15/9. The laminated bottom sediments are those of Sub-unit 4c, while the wavy layers at the surface are those of the surface layers of the accretion zone.



Fig. 3.25 Slightly calcareous quartz arenite of Sub-unit 4c. Sample 252, pit 15/9. Loose grains. X25.

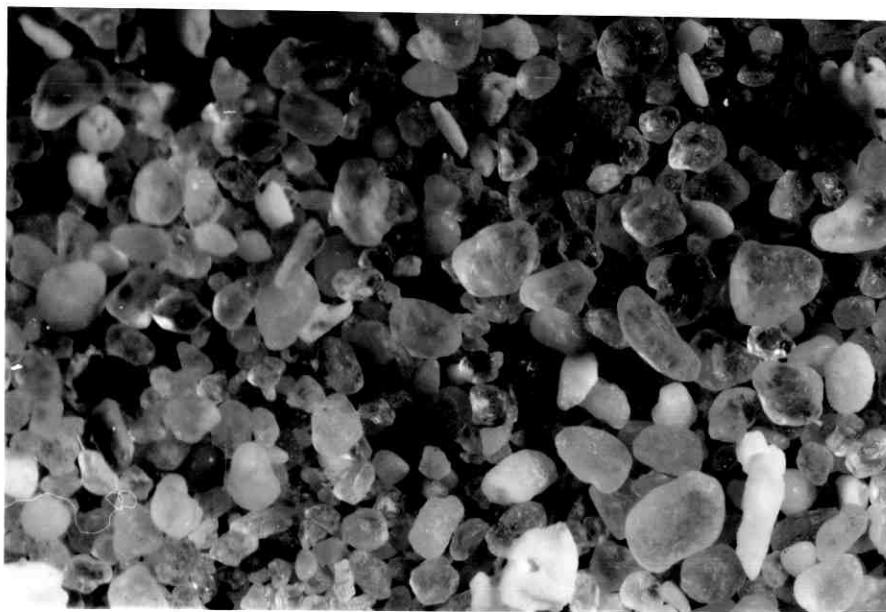


Fig. 3.26 Calcareous skeletal quartz arenite. Sample 258, pit 15/10.  
Loose grains. X25.

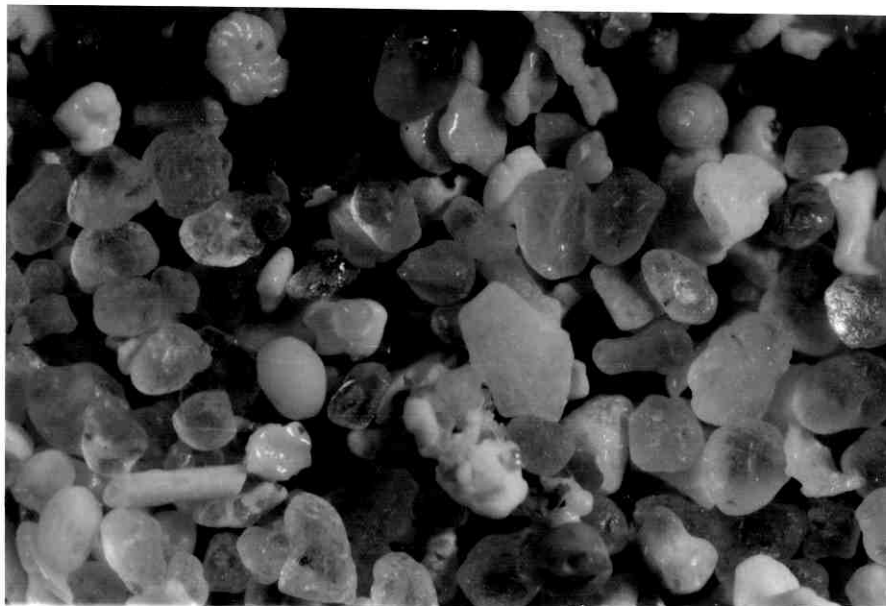


Fig. 3.27 Skeletal quartz arenite. Sample 268, pit 15/12. Loose grains. X25.

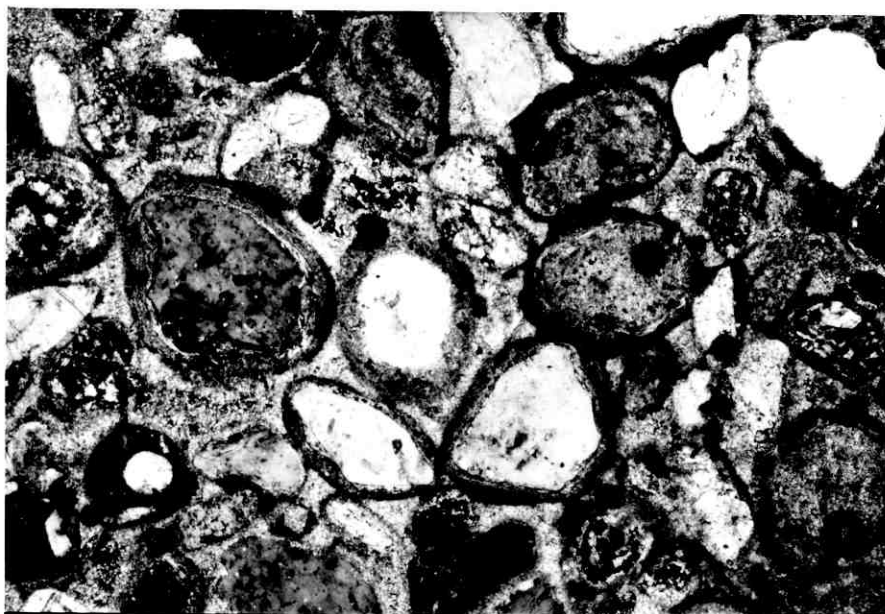


Fig. 3.28 Calcareous quartz arenite. Sample 268, pit 15/12. Impregnated loose grains. Crossed nicols. X90.

The sand grade material is composed of carbonate, quartz and gypsum grains. The carbonate grains are mainly coarse to medium sand grade, milky white peloids (Figs. 3.29, 3.30, 3.31, 3.32, 3.33 and 3.34) with some recognisable skeletal fragments (Figs. 3.31 and 3.33) and in some pits the sediments also include foraminiferal tests showing stages of alteration (Fig. 3.33).

The quartz grains are of coarse to medium sand grade and are rounded and subspherical (Fig. 3.29). Heavy minerals are present in very small amounts.

The gypsum grains are mainly coarse sand grade, and are discoidal in shape. The gypsum crystals found in the seaward area contain inclusions, but those inland do not.

Mineralogically, the sediments are composed of carbonate minerals, quartz, gypsum, celestite and feldspars having the following percentages (Figs. 3.92 - 3.101): carbonate minerals (37 - 91%); (aragonite (30 - 80%), calcite (2 - 6%), dolomite (1.5 - 6%), and high-magnesium calcite (0 - 6.5%)), quartz (5 - 60%), gypsum (0 - 10%), celestite (0 - 6%) and feldspars (0 - 4%). The silt plus clay grade material mainly consists of carbonate minerals.

### 3.5 The Surface Sediments, the Sediments of the Dunes and Salt Pan :

The following is a description of the sediments found on the surface of the previously described geomorphic units, the sediments of the dunes and the sediments of the salt pan, (see Section 2.2). Where the sediments of some pits vary from the previously described sedimentary units 1 to 4, a description of the vertical sedimentary sequence will be discussed.

#### 3.5.1 The Surface Sediments of the Ridges (Fig. 3.91):

The surface sediments of the beach ridges are part of Sub-unit 4b, but the top of the unit has a shell concentrate cover which is composed of the remains of Cerithid gastropods and bivalve fragments. Pits 15/15 and 15/5 which are located on different parts of the curving branch of the beach ridges (Fig. 3.91), contain sediments which are typical of Sub-unit 4b, but do not have the shell concentrate cover. At pit 15/5, Sub-unit 4b is overlaid by a 0.2m. thick bed which consists of loose, homogenous, poorly sorted, coarse sand grade gypsum crystals

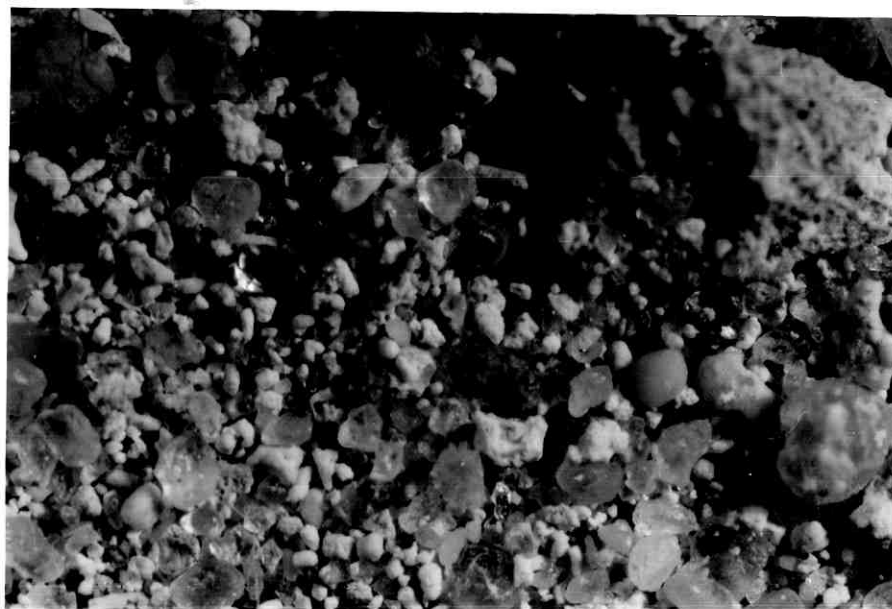


Fig. 3.29 Quartzose calcarenite. Sample 475, pit 15/14. Note peloids.  
Loose grains. X25.

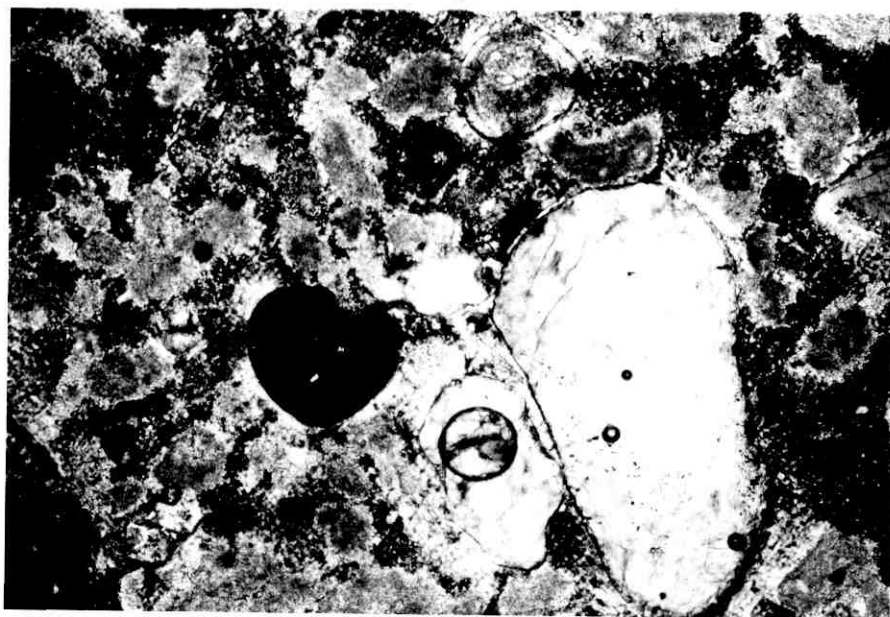


Fig. 3.30 Quartzose calcarenite. Sample 401, pit 15/17. Note altered  
carbonate grains. Impregnated grains. Crossed nicols. X90.



Fig. 3.31 Quartzose calcarenite. Sample 480, pit 15/16. Note peloids and worn skeletal fragments. Loose grains. X25.

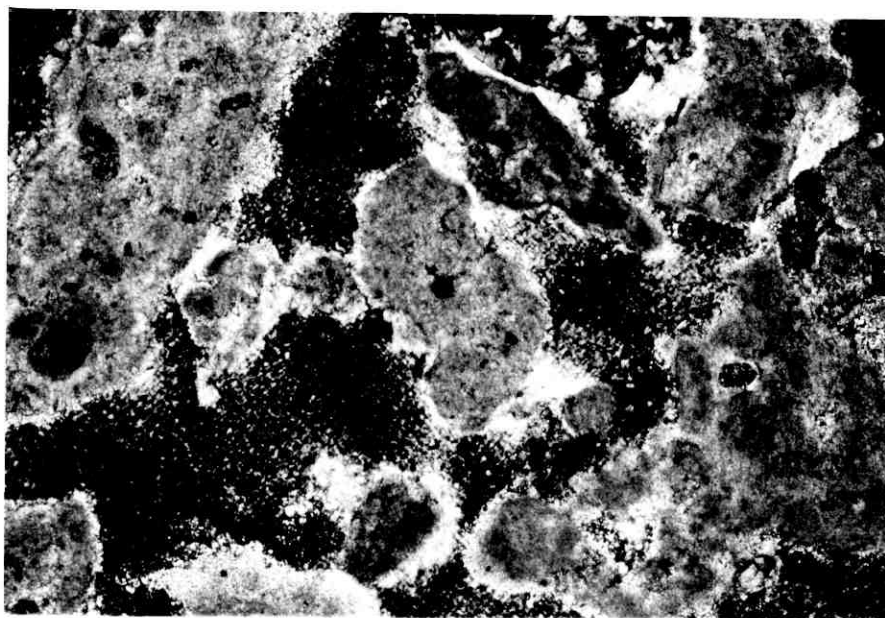


Fig. 3.32 Thin section of sample 480, pit 15/16. Note alternation of carbonate grains. Impregnated grains. Crossed nicols. X90.

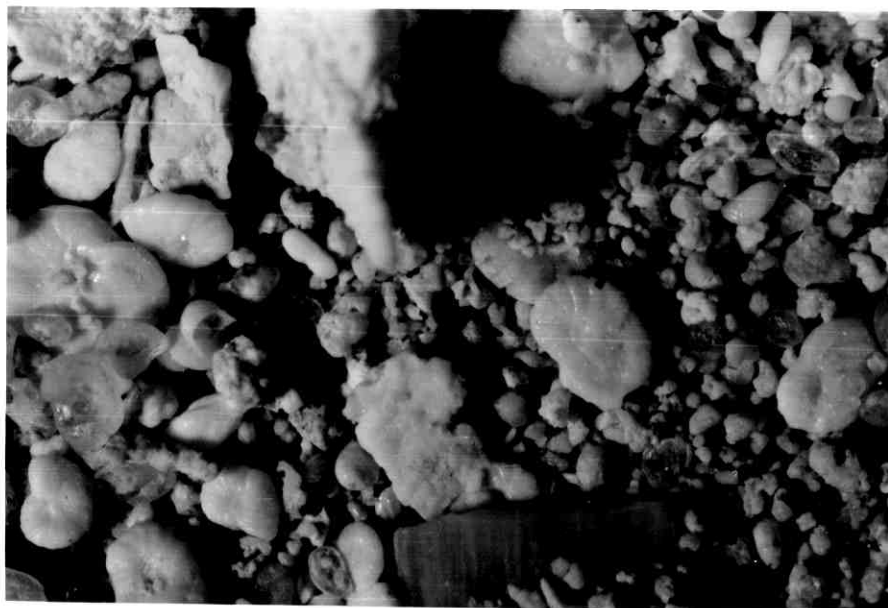


Fig. 3.33 Peloids, worm skeletal fragments and foraminiferal tests, Sample 482, pit 15/16. Loose grains. X25.

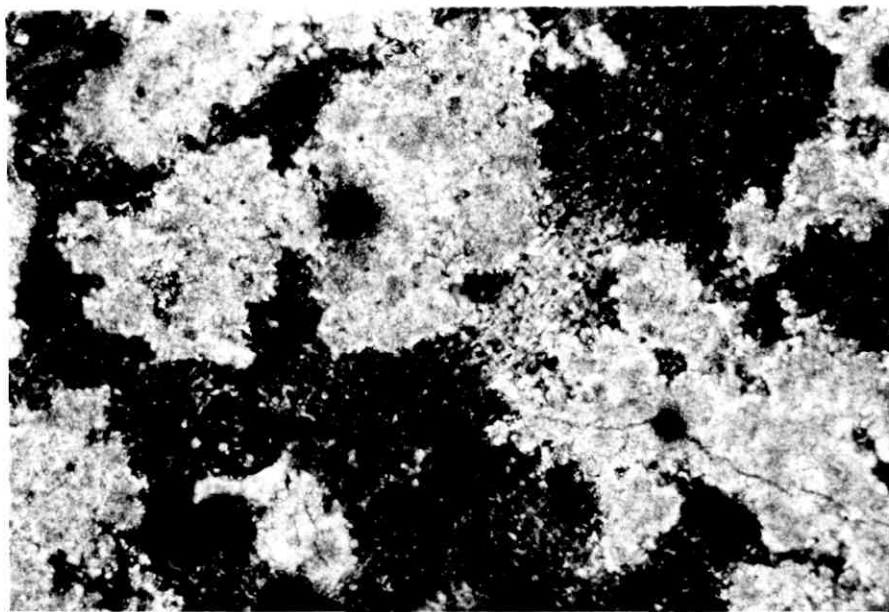


Fig. 3.34 Altered carbonate grains. Sample 675, pit 15/6. Impregnated grains. Crossed nicols. X144.

(from the pit description, this material appears similar to the surface layer of the dune at pit 15/6, which will be discussed later).

The surface sediments of the inner ridge (pit 13/61), west of the salt pan (Fig. 3.91), are pale orange, moderately sorted, medium to fine slightly calcareous quartz arenite, which is similar to Unit 2, and has a thickness of 40mm. There are few aggregates composed of quartz and carbonate grains cemented together by a calcareous cement, and there are one or two gravel grade skeletal fragments having their original colours and textures, and a very few foraminiferal tests showing stages of alteration from porcellaneous to milky white under reflected light. Mineralogically this layer is similar to Unit 2 (see Section 3.2 and Figs. 3.92 to 3.101).

### 3.5.2 The Surface Sediments of the Sabkha (Fig. 3.91):

The surface sediments of the sabkha (Fig. 3.91) are of Unit 2 type, calcareous quartz arenites. In some pits this unit is overlain by a layer of sediments having a maximum thickness of 100mm. (Fig. 3.91), consisting of a very dark yellowish orange, moderately sorted, coarse to fine gypseous calcareous quartz arenite. The sediments are loose, homogenous and have a percentage of silt plus clay grade material ranging from 20 to 26% (Fig. 3.102).

The sediments are similar to those of Unit 2, apart from the presence of gypsum (6 - 18%). Gypsum is mainly present as discoidal poikilotopic and displacive crystals. The poikilotopic crystals are more abundant and are generally of very coarse to coarse sand grade, cloudy, and rounded. The displacive crystals are generally of coarse sand grade, clear to translucent and with better developed crystal faces than the poikilotopic crystals. There are also a few coarse sand grade gypsum grains, aggregates and cleavage flakes; the gypsum grains are anhedral, the aggregates consist of medium sand grade sugar-like gypsum crystals which are translucent, and the gypsum cleavage flakes are of medium to fine sand grade and are translucent. Celestite (1 - 4%) is present in the more landward parts.

### 3.5.3 The Surface Sediments of the Accretion Zone (Fig. 3.91):

The surface sediments of the accretion zone have been encountered in some pits in profiles V - VI and IX - X (Fig. 3.91). The sediments grade in a landward direction from gypseous calcareous quartz arenites, to calcareous gypseous quartz arenites, to slightly calcareous quartzose

gypsarenites, the specific characteristics of each of which are now described.

Towards the sea, (pits 15/9, 15/10 and 15/27), the surface sediments are grayish orange, moderately sorted, medium gypseous calcareous quartz arenites. The sediments are loose and layered, at pit 15/9 gypsum forms wavy layers (Fig. 3.24). The percentage of silt plus clay grade ranges from 1 to 7%, increasing in an inland direction (Fig. 3.102).

The sand grade material consists of quartz, carbonate, gypsum and heavy mineral grains. The quartz grains are of two types: the majority are of medium to fine sand grade, subangular, subrounded and a few grains have patches of carbonate coating and a few are coarse sand grade quartz grains which are rounded, spherical and frosted. The carbonate grains are of coarse to medium sand grade, milky white peloids with a very few milky white skeletal fragments. The gypsum grains are generally of coarse sand to gravel grade, and are mainly clear discoids with well developed crystal faces. Some gypsum crystals are twinned and others are slightly cloudy but with a thin clear periphery and look slightly worn. A very few grains are anhedral, gravel grade, gypsum, some of which appear to be discoids with a bulky overgrowth. These types of gypsum grains are absent at pit 15/10, where gypsum is present as anhedral grains, some of which are cleavage flakes and elongated gypsum grains. Gypsum is also present as coarse sand grade sugar-like crystals. Magnetite, blue and green amphiboles and other heavy minerals are present in the fine sand grade.

Further inland at pits 15/13, 15/14 and 15/24, the surface sediments are pale yellowish brown, poorly sorted, bimodal (gravel to coarse sand grade and medium to fine sand grade), calcareous gypseous quartz arenites. The sediments are loose and homogenous apart from the presence of gypsum nodules. The percentage of silt plus clay grade material ranges from 15 to 17% increasing inland.

The sand grade material is similar to that of the previously described sediments apart from a notable increase in gypsum. The gypsum grains are coarse sand to gravel grade, increasing in size in an inland direction. The gypsum grains are anhedral and discoidal crystals (Figs. 3.35 and 3.36). The discoidal crystals appear worn with rounded edges and some are broken (Figs. 3.35 and 3.36), and they also have a surface



Fig. 3.35 Calcareous gypseous quartz arenite. Sample 394, pit 15/13.  
Note milky white peloids and fine gravel grade, worn, gypsum discoids. Loose grains. X25.

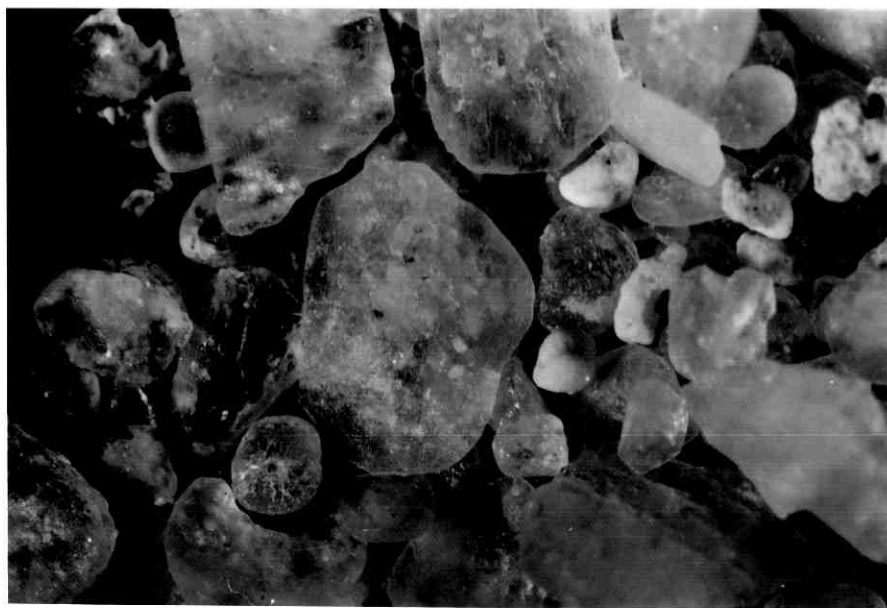


Fig. 3.36 Calcareous gypseous quartz arenite. Sample 474, pit 15/14.  
Note gravel grade, worn, gypsum discoids and anhedral gypsum grains. Loose grains. X25.

feature which is similar to frosting (Figs. 3.35 and 3.36) and is probably due partly to the impact with other grains and partly to solution. Some gypsum crystals and grains enclose some of the host sediments.

Mineralogically, the surface sediments of the previously described pits consists of quartz, carbonate minerals, gypsum and feldspar having the following ranges of percentages (Figs. 3.92 - 3.101): quartz (58 - 73%), carbonate minerals (5.5 - 22%); (calcite (4 - 14%), high-magnesium calcite (1.5 - 2%) and dolomite (2 - 7%)), gypsum (3 - 33%) and feldspars (2.5 - 7%). Calcite, dolomite and feldspars gradually decrease in an inland direction. The amount of carbonate minerals and gypsum present in the sand grade is less than is suggested by the mineralogical analysis, so they must also be present in the silt plus clay grade materials.

Further inland at pit 15/16 the top 250mm. can be divided into two beds: the lower bed is 150mm. thick and consists of an orangey yellowish gray, moderately sorted, bimodal (gravel grade to coarse sand grade and mud) anhydritic gypseous quartz arenite. The sediments are soft, layered with anhydrite rich layers in a gypseous matrix, and have a percentage of silt plus clay grade material of 49.5% (Fig. 3.102). The quartz grains are generally very coarse to coarse sand grade, rounded, spherical and frosted (Figs. 3.39 and 3.40). Gypsum is mainly present as clear, coarse sand grade discoidal crystals, plus a few clear and subhedral needles and short rods, and anhedral gypsum grains. Anhydrite is present as gravel grade to coarse sand grade nodules (Figs. 3.39 and 3.40). Carbonate grains are not common, and are mainly peloids. There are very few heavy mineral grains. Mineralogically the sediments are composed of (Figs. 3.92 - 3.101): quartz (45%), gypsum (24%), anhydrite (12%), carbonate minerals (8%); (calcite (6.5%), dolomite (2.5%) and magnesite (0.17%)), celestite (4%) and feldspars (4%). The amount of gypsum, anhydrite and carbonates seen in the sand grade is less than is suggested by the mineralogical analysis so they must also be present in the silt plus clay grade material.

The surface layer is 100mm. thick, and consists of a pale grayish orange, moderately sorted, bimodal (medium sand and mud) anhydritic gypseous quartz arenite. The sediments are soft, with lenses and nodules of anhydrite, and have a silt plus clay grade percentage of 35%. The quartz, carbonate, and heavy mineral grains are similar to other surface



Fig. 3.37 Anhydritic gypseous quartz arenite. Sample 478, pit 15/16.  
Note platy anhydrite lathes. Loose grains. X25.

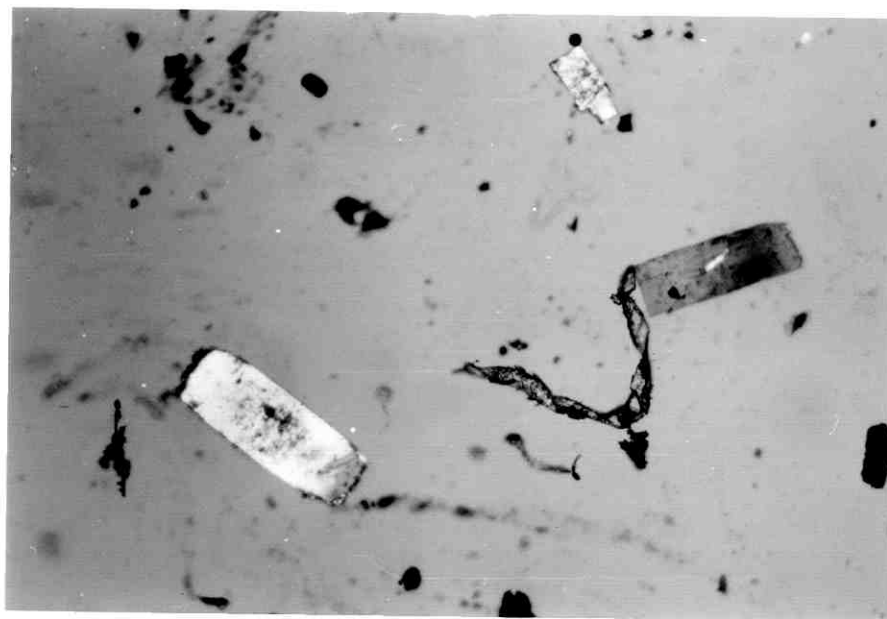


Fig. 3.38 Coarse anhydritic laths. Sample 478, pit 15/16. Loose  
grains. Crossed nicols. X90.

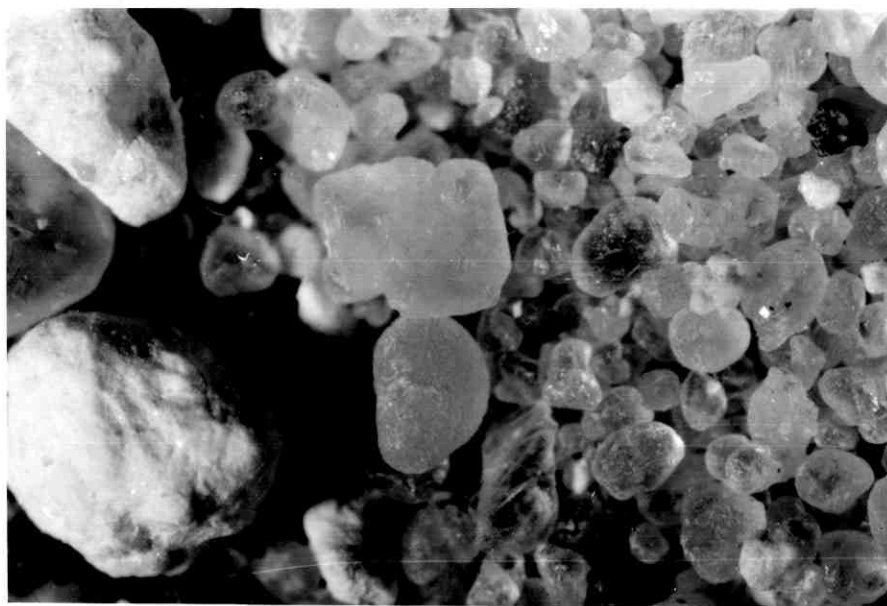


Fig. 3.39 Anhydritic gypseous quartz arenite. Sample 479, pit 15/16. Note anhydritic nodules and anhedral gypsum grains. Loose grains. X25.

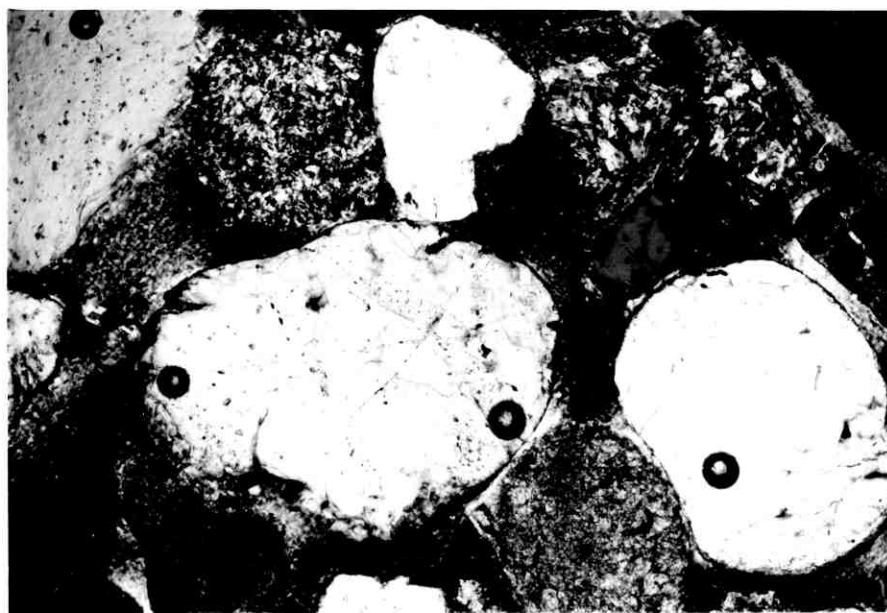


Fig. 3.40 Anhydritic nodules and coarse sand grade, rounded, quartz grains. Sample 479, pit 15/16. Impregnated grains. Crossed nicols. X 90.

sediments on this unit (Fig. 3.37). Anhydrite is present as individual laths of coarse to medium sand grade, which are platy (Fig. 3.37 and 3.38) and are similar to those described by Shearman, 1978. Mineralogically, the sediments consist of (Figs. 3.92 - 3.101): quartz (40%), gypsum (28.5%), anhydrite (25%), carbonate minerals (3.5%): (calcite (2%) and dolomite (1.5%)) and feldspars (3%). Gypsum and anhydrite are also present in the silt plus clay grade material.

Still further inland at pits 15/17, 15/18 and 15/19, the surface sediments are pale yellowish brown, poorly sorted, rudaceous, coarse calcareous quartzose gypsarenite. The sediments are loose and homogenous apart from some gypsum nodules, and have a silt plus clay grade percentage ranging from 0 - 18% (Fig. 3.102). Gypsum is mainly present as gravel grade, cloudy anhedral grains containing inclusions and having patchy carbonate coatings (Fig. 3.41), and gravel grade, cloudy discoids which are sometimes worn and broken (Fig. 3.41). Gypsum is also present as clear and subhedral medium sand grade discoids and cleavage flakes. At pit 15/19 anhedral gravel grade grains are not present and twinned gypsum crystals are common. Quartz grains are of medium sand grade, with very few of coarse sand grade. Carbonates are generally coarse to medium sand grade milky white peloids and skeletal fragments (Fig. 3.41). Blue and green amphiboles and other heavy minerals are present in the fine sand grade.

Mineralogically the sediments (Figs. 3.92 - 3.101) consist of: gypsum (67 - 85%), quartz (7 - 22%), carbonate minerals (7 - 9%); (calcite (2 - 7%) and dolomite (0 - 3%)), celestite (0 - 6%) and feldspars (1 - 2%). The high silt plus clay material (18%), high carbonate (9%), lower gypsum (67%) and higher quartz percentages (22%) are present in the sediments of pit 15/19.

At this point it is appropriate to discuss the vertical sedimentary sequence of pit 15/19, where the surface and bottom gypsum beds are similar, and enclose between them gypsum of a different crystal habit.

This intermediate bed consists of a very pale orange, poorly sorted, gypsum ruditic coarse gypsarenite. The sediments are loose and homogenous apart from the presence of gypsum nodules. Gypsum crystals are mainly gravel grade to coarse sand grade needles and rods, the gravel grade crystals tend to lose their shape where there

are overgrowths, as the growth is unevenly distributed, in addition both the gravel grade and coarse sand grade gypsum crystals are corroded. The medium to fine sand grade gypsum crystals are generally anhedral, but few are corroded. A very few gypsum flakes are present. Carbonate and quartz grains are not common.

Mineralogically the sediments (Figs. 3.92 - 3.101) consist of: gypsum (95%), calcite (4%) and quartz (1%).

#### 3.5.4 The Surface Sediments of the Platform (Fig. 3.91):

The surface sediments of the platform have been encountered in some pits in profiles I - II, V - VI and IX - X (Fig. 3.91), being quartzose skeletal calcarenites at profile I - II, and skeletal calcareous quartz arenites at profiles V - VI and IX - X.

At pit 11/28 the surface sediments are calcareous cemented (Fig. 3.42) quartzose skeletal calcarenite, and are similar to the sediments of Sub-unit 3a (see Section 3.3.1). The surface here is polygonally patterned. A very small amount of gypsum is also present.

Further inland at pits 13/1 and 13/2 the surface sediments have a calcareous gypsarenite layer which was not sampled.

At pits 15/11 and 15/12, profile V - VI, the sediments are grayish orange, moderately sorted fine to medium calcareous quartz arenites. These sediments are similar to those making up Unit 2, apart from the presence of gypsum (7%) in the sediments of pit 15/11; gypsum crystals are coarse sand grade displacive and poikilotopic discoids. The displacive discoids are euhedral to subhedral, and there are also a very few short rods and cleavage flakes. At pit 15/11 the sediments have a silt plus clay grade percentage of 26%, while at pit 15/12 there is not silt or clay.

Mineralogically the sediments consist of quartz, carbonate minerals, gypsum and feldspars have the following percentages (Figs. 3.92 - 3.101): quartz (65 - 75%), carbonate minerals (23%); (calcite (7 - 14%), aragonite (0 - 12%), high-magnesium calcite (2 - 5%), and dolomite (1 - 4%)), gypsum (0 - 7%) and feldspars (2 - 7%).

At pits 15/25 and 15/26, profile IX - X, the sediments are very

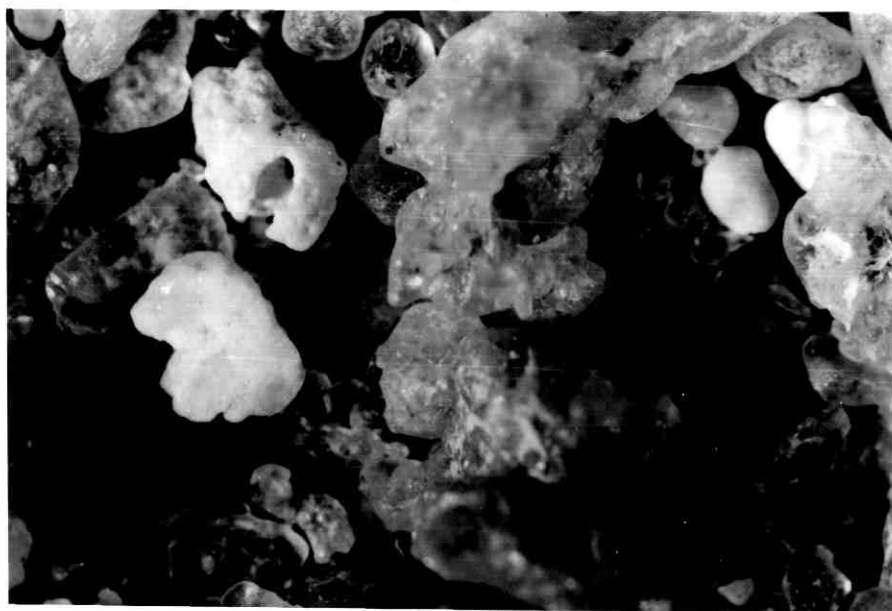


Fig. 3.41 Gravel grade, anhedral gypsum and altered carbonate grains.  
Sample 400, pit 15/17. Loose grains. X25.

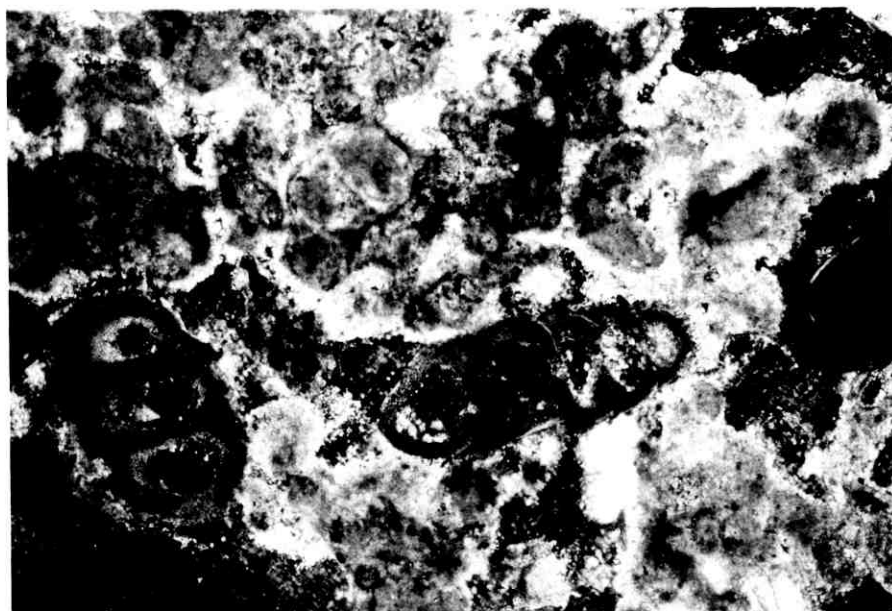


Fig. 3.42 Cemented skeletal calcarenite. Sample 1093, pit 11/28.  
Note peloids and foraminiferal tests. Impregnated grains.  
Crossed nicols. X90.

pale yellowish brown, poorly sorted, bimodal (gravel grade to coarse sand grade and medium to fine sand grade) skeletal quartz arenites. The sediments are loose, with layers and lenses of gravel grade Molluscan shells. The percentage of silt plus clay grade material ranges from 7 to 12%. The sediments are similar to those making up Sub-unit 4b, apart from the uppermost 100mm, of pit 15/25, where the gravel grade Molluscan shells decrease in amount, peloids become more common and gypsum is present as very coarse to coarse sand grade anhedral grains and worn and broken discoids some of which contain inclusions.

Mineralogically the sediments consist of (Figs. 3.92 - 3.101): quartz (60 - 70%), carbonate minerals (23 - 36%); (aragonite (18 - 28%), calcite (3 - 5%), high-magnesium calcite (0.5 - 2%) and dolomite (1%)), gypsum (0 - 6%), celestite (1 - 3%) and feldspars (1%).

### 3.5.5 The Sediments of the Dunes:

In discussing the sediments of the dunes, the aeolian sands with dune forms which have built upon the backslope will be dealt with first, followed by the sediments of the other dunes in the area of study. In most cases only the surface sediments will be discussed as the underlying sediments of the sedimentary sequence are similar to those of the previously described Units 1 to 4 (Fig. 3.91); where this is not true, the whole sedimentary sequence will be discussed.

#### 3.5.5.a Aeolian Sands with Dune Forms:

At pits 13/3, 13/83 and 15/6 (Fig. 3.89) the surface sediments are moderate yellowish brown, moderately to poorly sorted, rudaceous to coarse calcareous quartzose gypsarenites. The sediments are loose and homogenous apart from pit 13/3 where there are gravel grade aggregates composed of gypsum, quartz and carbonate grains cemented by a coarse gypseous cement (Fig. 3.43) which in parts is poikilotopic, and have a percentage of silt plus clay grade material of 4 to 7% (Fig. 3.102). The sediments are composed of gypsum, quartz, carbonate and heavy mineral grains. The gypsum grains are of gravel grade to coarse sand grade, anhedral (Fig. 3.45), worn and broken, some look like discoids, some are cloudy and others are poikilotopic (Fig. 3.44). Quartz grains are of coarse to medium sand grade and carbonate grains are mainly present as coarse sand grade skeletal fragments. There are also a very few green amphiboles, opaque grains and other heavy mineral grains.

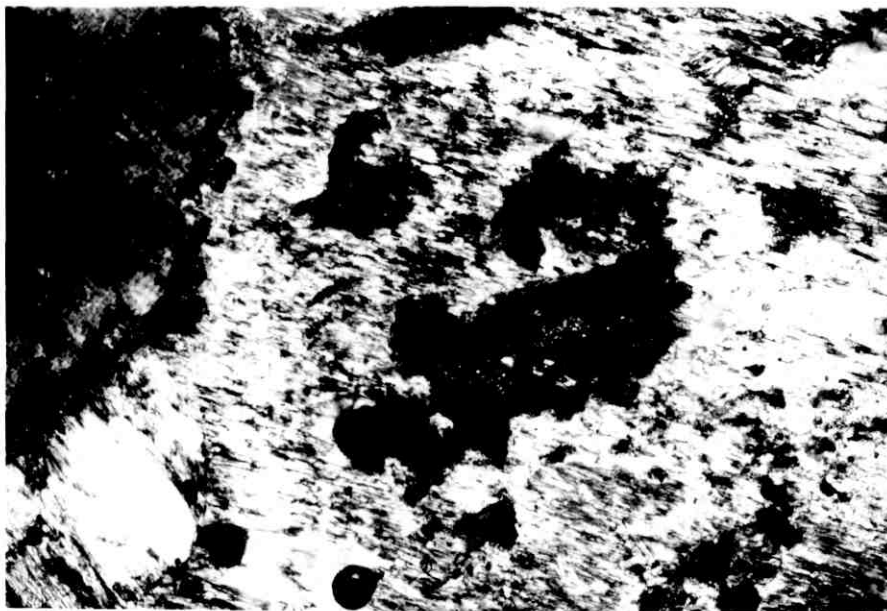


Fig. 3.43 Coarse gypsum cement. Sample 1106, pit 13/3. Impregnated rock. Crossed nicols. X90.

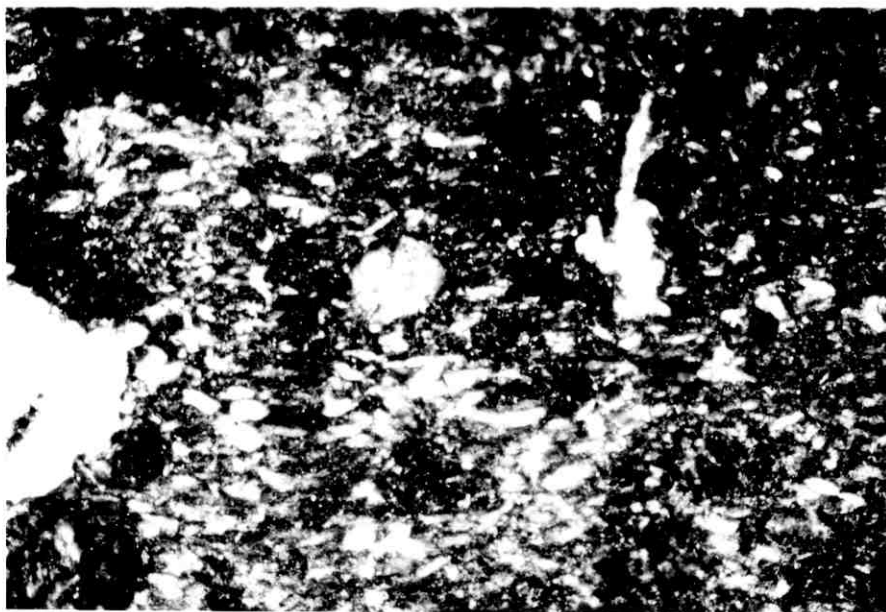


Fig. 3.44 Gravel grade, poikilotopic, gypsum grain. Sample 1106, pit 13/3. Impregnated grains. Crossed nicols. X90.



Fig. 3.45 Gravel grade, anhedral gypsum grains. Photo to show shape of grains, as gypsum has been plucked out during the making of the thin section. Impregnated grains. X90.

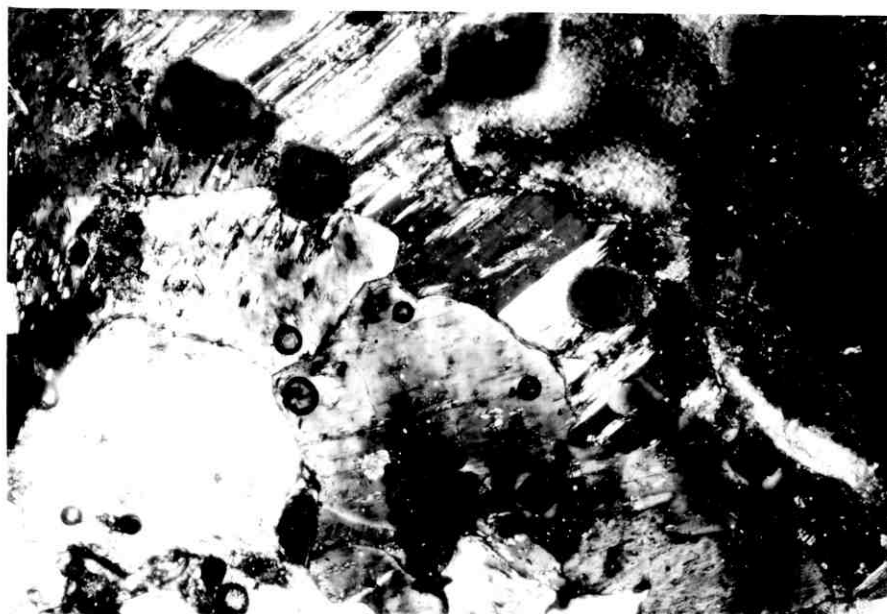


Fig. 3.46 Gravel grade to coarse sand grade poikilotopic gypsum cement. Sample 1085, pit 11/27. Impregnated rock. Crossed nicols, X90.

Mineralogically the sediments consist of (Figs. 3.92 - 3.101): gypsum (60 - 70%), quartz (17 - 30%), carbonate minerals (6 - 11%); (calcite (5 - 11%) and high-magnesium calcite (1%)) and feldspars (1%). Celestite is present in the sediments of pit 13/3, ranging from 1.9 to 3.6%.

At pit 15/22 (Fig. 3.91) the surface sediment is a light brownish olive gray, poorly sorted, bimodal (mainly lutite with some coarse to medium sand grade) calcareous anhydritic quartz lutite. The sediments are soft and homogenous and have a percentage of silt plus clay grade material of 72% (Fig. 3.102). The sand grade material consists of the following: quartz grains of coarse to medium sand grade, some of which have a slight carbonate coating. Carbonate grains of coarse to fine sand grade, consisting of milky white peloids and some skeletal fragments. Gypsum is not abundant and is present as coarse to medium sand grade cloudy discoids. Anhydrite is not present in the sand grade sediments but was detected by XRD, so it is present in the silt plus clay grade fraction. Heavy minerals are present in the fine sand grade in small amounts.

Mineralogically the sediments consist of (Figs. 3.92 - 3.101): quartz (42%), anhydrite (30%), carbonate minerals (21%); (calcite (15.5%) and dolomite (5.5%)), gypsum (3.5%) and feldspars.

This surface unit is covered by a 10mm. thick cemented crust which consists of a very pale orange, poorly sorted, coarse calcareous quartz arenite. The quartz grains have a carbonate coating and the carbonate grains consist of peloids and skeletal fragments.

Mineralogically the sediments of the crust consist of (Figs. 3.92 - 3.101): quartz (50%), aragonite (38%), calcite (2%), celestite (5%), high-magnesium calcite (2%), dolomite (1.5%) and feldspars (1.5%).

#### 3.5.5.b The Sediments of the Dunes:

Pit 11/27, profile I - II, was dug in a nebkha, and the surface sediments consist of a grayish orange, poorly sorted, very coarse quartzose calcareous gypsarenite. The sediments are loose to weakly cemented (the cement is gravel grade to coarse sand grade poikilotopic gypsum (Fig. 3.46), and homogenous. The sediments are similar to those of pits 13/3 and 15/6, apart from a decrease in the gypsum content and an increase in the

carbonate content, the carbonate grains consist of gravel grade skeletal fragments and fine to medium sand grade milky white peloids. Heavy minerals are present in small amounts.

Mineralogically the sediments consist of (Figs. 3.92 - 3.101): gypsum (44%), aragonite (24%), quartz (20.5%), calcite (8%) and dolomite (3.5%).

The following section is a description of other dunes present within the area of study, but not in the profiles (for their statistical parameters and mineralogy see Appendices 1 and 2).

At pits 13/17, 13/18, 13/28, 13/37 and 13/38 (Fig. 3.89), the surface sediments are pale grayish orange, moderately sorted, coarse to medium gypseous calcareous quartz arenites. The sediments are loose and laminated and have a percentage of silt plus clay grade material mainly of less than 1%. The quartz grains are mainly of coarse sand grade, rounded, spherical and frosted, with some medium sand grade quartz grains. Carbonate grains are mainly coarse sand grade, worn skeletal fragments and peloids. Gypsum is mainly present as coarse sand grade anhedral grains and discoids some of which are broken (Fig. 3.47). Magnetite, green amphiboles and other heavy mineral grains are present in the fine sand grade. Also present are a very few plant roots.

Mineralogically the surface sediments of the dunes consist of (Appendix 1): quartz (66 - 83%), carbonate minerals (13 - 23%); (calcite (10 - 13.5%), aragonite (0 - 7.5%), dolomite (1 - 3.5%) and high-magnesium calcite (0 - 2%)), gypsum (0 - 15.5%) and feldspars (1.5 - 4.5%).

### 3.5.6 The Sediments of the Salt Pan (Mamlahat al Mumattalah):

The following section is a discussion of the sedimentary sequences present in the salt pan. The polygonal patterned ground in the north of the pan was neither surveyed nor sampled.

#### 3.5.6.I The Sediments at the Centre of the Pan (profile III - IV, Figs. 3.91, 3.48, 3.49, 3.50 and 3.51):

Four sedimentary sub-units are identified and discussed in the following section, these are from bottom to top:-

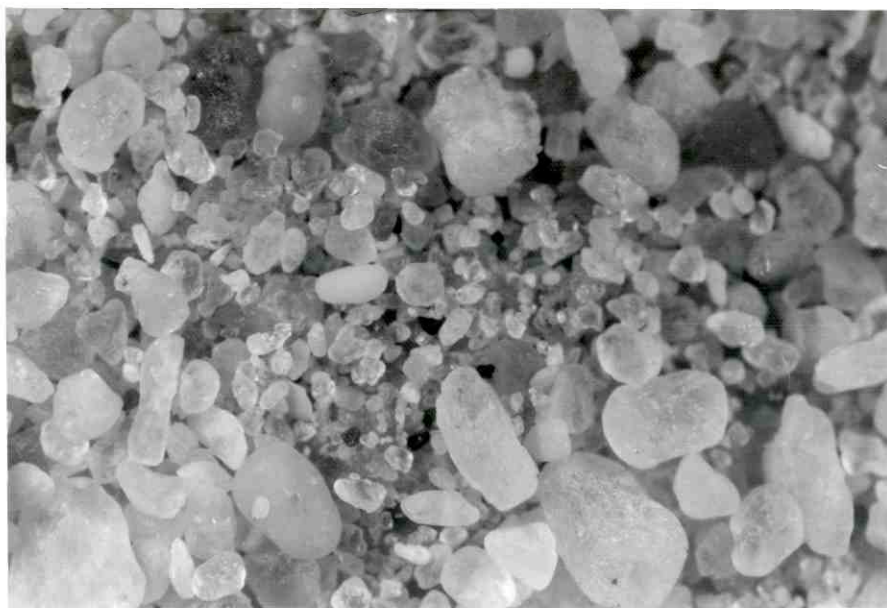


Fig. 3.47 Calcareous gypseous quartz arenite. Sample 1125, pit 13/38.  
Note anhedral gypsum grains, and rounded gypsum grains.  
Loose grains. X25.

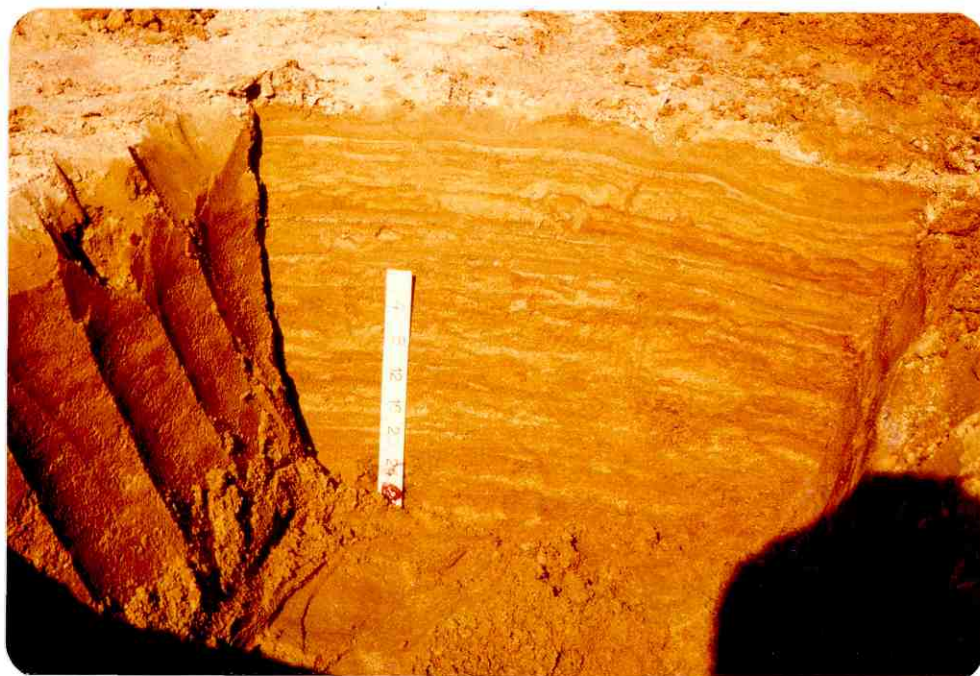


Fig. 3.48 Pit 13/44 in the salt pan. Note wavy layers of gypsum.



Fig. 3.49 Pit 13/46 in the salt pan. Note gas bubbles in the groundwater.

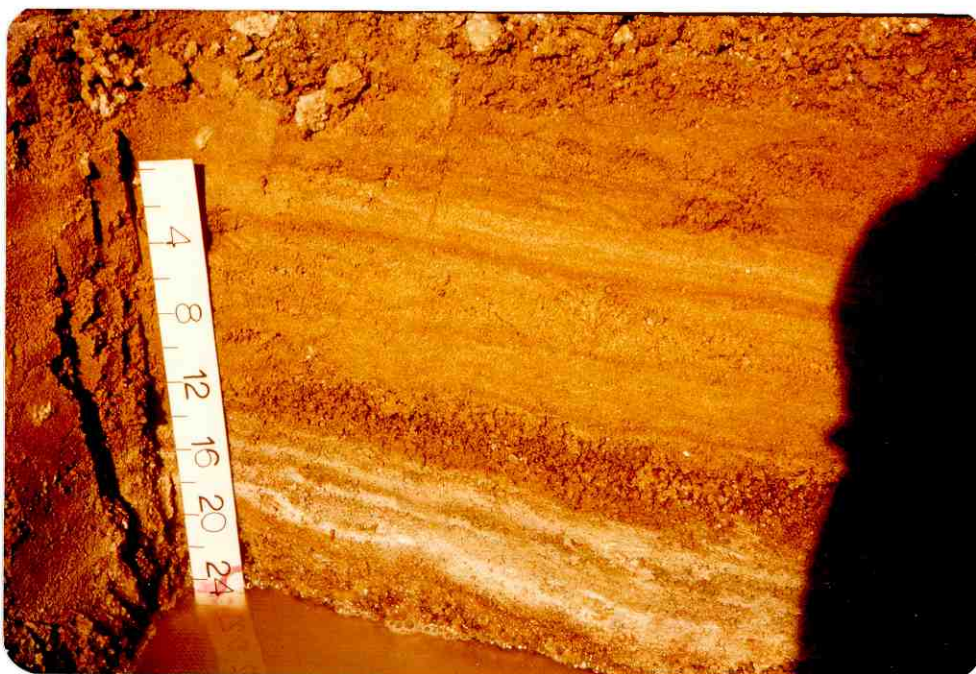


Fig. 3.50 Pit 13/49 in the salt pan.



Fig. 3.51 Pit 13/52 in the salt pan. Note gas bubbles in the groundwater.



Fig. 3.52 Anhydrite nodules of Sub-unit a. Sample 375, pit 13/45. Loose grains. X25.

### 3.5.6.a.1 Sub-unit a (Fig. 3.91):

The sediments of this sub-unit consist of white, poorly sorted nodular anhydrite with quartz and gypsum. The sediments occur below the water-table, therefore the base of this sub-unit was never reached and its thickness is not known. The sediments are soft and homogenous. The silt plus clay grade material ranges from 33 to 57% (Fig. 3.102). The anhydrite nodules (Fig. 3.52) vary in size from gravel grade to coarse sand grade, also present are individual laths of anhydrite. Some of the gravel grade nodules contain coarse laths of anhydrite at their surfaces, and some nodules contain the host sediments either at the surface or within the nodules. There are a few gypsum needles in the fine sand fraction which are corroded in the sediments of pit 13/46 and are less corroded towards the east. At pit 13/52 coarse to medium sand grade discoidal gypsum are present. Quartz grains are generally not abundant in the sediments apart from the sediments of pit 13/46 where they are abundant and are of a coarse to medium sand grade. Carbonate grains are present in small amounts and are very difficult to detect.

Mineralogically the sediments consist of (Figs. 3.92 - 3.101): anhydrite (84 - 99%), gypsum (0 - 7%) and quartz (0 - 13%).

### 3.5.6.a.2 Sub-unit b (Fig. 3.91):

The sediments of this sub-unit consist of pinky yellowish gray, poorly sorted, gypsum ruditic coarse gypsarenite. This sub-unit occurs above the groundwater table, and has a thickness varying from 50 to 120mm. (Fig. 3.91). The sediments were not sampled towards the east of the pan, but from the pit descriptions it appears that they are similar to those occurring towards the west of the pan, and are loose and homogenous. The silt plus clay grade material ranges from 6 to 10% (Fig. 3.102).

The sediments are mainly gravel grade to coarse sand grade corroded gypsum needles and rods (Fig. 3.53). There are two types of needles: some needles have four faces parallel to the C-crystallographic axis, while others have six faces parallel to the C-crystallographic axis. Also present are short selenite habit, crystals, which tend to look like a stage between gypsum needles and discoids. A gypsum overgrowth tends to mis-shape the rods and needles of gypsum. Coarse sand grade displacive discoidal gypsum crystals are also present.

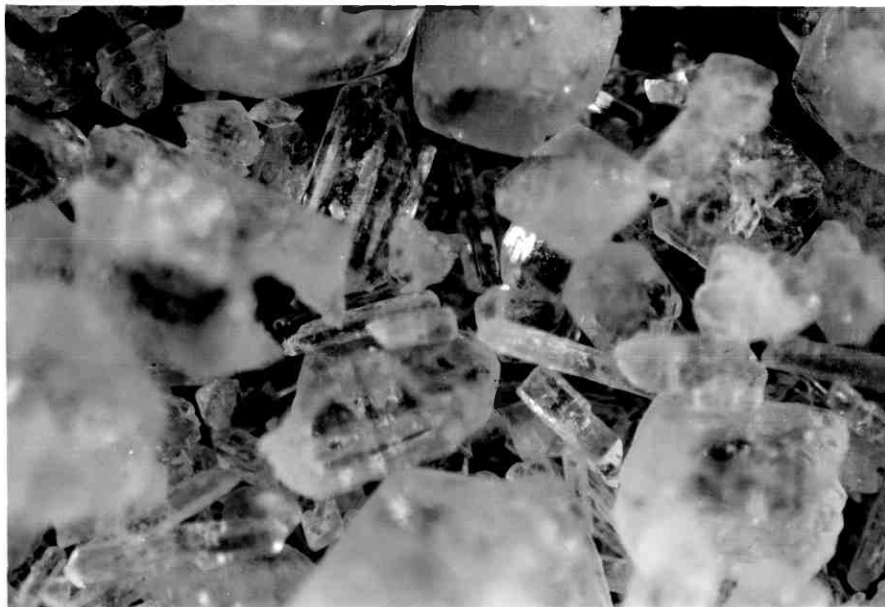


Fig. 3.53 Gypsarenite. Sample 374, pit 13/45. Note corroded needles, discoidal crystals and short, selenite habit crystal. Loose grains. X25.



Fig. 3.54 Sample 380, pit 13/46. Note cloudy, poikilotopic gypsum discoids, which are worn and rounded. Loose grains. X25.

Mineralogically the sediments consist of (Figs. 3.92 - 3.101): gypsum (97%) and anhydrite (3%). Anhydrite is present in the silt plus clay grade, as it was not detected in the sand grade.

#### 3.5.6.a.3 Sub-unit c (Fig. 3.91):

The sediments of this sub-unit consist of pale brownish gray, poorly sorted, slightly gravelly, coarse calcareous quartzose gypsarenite. This sub-unit was only sampled from pit 13/46, but according to the pit descriptions occurs in the sediments of the pits towards the east having a thickness varying from 33 to 120mm. The silt plus clay grade material ranges from 5 to 16% (Fig. 3.102).

The gypsum present has various habits; the most abundant type is of coarse sand grade, with some gravel grade, clear displacive gypsum discoids. Next in abundance are the coarse to medium sand grade, clear needles and rods of gypsum. The least abundant are the short, selenite habit, crystals, and cloudy poikilotopic discoidal crystals which are worn and rounded (Fig. 3.54). Quartz grains are mainly fine to medium sand grade. Carbonates are mainly medium to fine sand grade peloids with a very few skeletal fragments. Heavy minerals are present in small amounts in the fine sand fractions.

Mineralogically the sediments consist of (Figs. 3.92 - 3.101): gypsum (78%), quartz (16%), calcite (4%) and anhydrite (2%).

#### 3.5.6.a.4 Sub-unit d (Fig. 3.91):

Sub-unit d is the surface unit, and consists of pale yellowish brown, poorly to moderately sorted, medium to fine calcareous gypseous quartz arenites. The sediments are loose, and gypsum forms wavy layers (Fig. 3.48). The silt plus clay grade material ranges from 6 to 21% (Fig. 3.102).

The sediments mainly consist of quartz grains which are of a medium to fine sand grade, subspherical, subrounded, and the coarser grade quartz grains are frosted. A very few coarse sand grade quartz grains are also present some of which have patches of carbonate coating. Gypsum crystals of different habits are present in the sediments: they are mainly coarse to medium sand grade discoids, cloudy to clear, some cloudy discoids have a hexagonal shape. Less abundant are short, selenite habit, crystals, needles, rods and anhedral grains (Fig. 3.55)

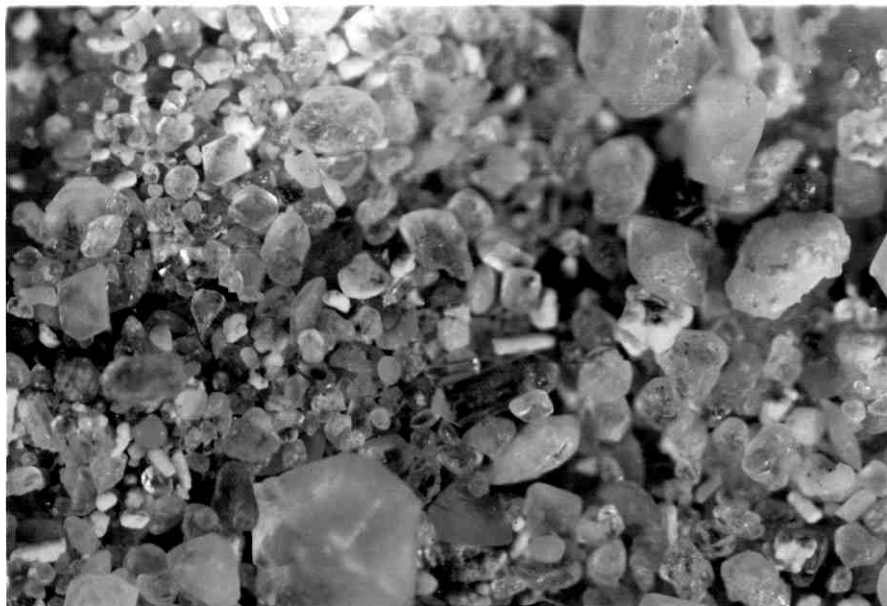


Fig. 3.55 Calcareous gypseous quartz arenite. Sample 381, pit 13/46  
Loose grains. X25.



Fig. 3.56 Hemihydrate and anhydrite. Sample 372, pit 13/44. Anhydrite  
and hemihydrate were both detected by the XRD technique, as  
it is difficult to differentiate between them under the  
binocular microscope. Loose grains. X25.

which become more abundant towards the east of the pan. Hemihydrate has been detected by XRD from most of the sediments of Sub-unit d, but its percentage is not taken into account by the computer programme (of Bush, 1973). At pit 13/44 (the patterned ground west of the salt pan) with an increase in depth, there are chalky white grains of hemihydrate (Fig. 3.56) which are similar to the 'dead-burnt gypsum' described by Shearman, 1979. Carbonate grains are generally milky white, medium sand grade peloids with a very few skeletal fragments and pellets (Fig. 3.55) and tend to increase slightly towards the margin of the pan. Magnetite, green amphiboles and other heavy minerals are present in the fine sand grade sediments.

Mineralogically the sediments consist of (Figs. 3.92 - 3.101): quartz (40 - 55%), gypsum (25%), calcite (9 - 13%), aragonite (18%, present in pit 13/46 only), high-magnesium calcite (2 - 5%), dolomite (3%), feldspars (2 - 5%) and anhydrite (0 - 2%). Hemihydrate is present, but its percentage has not been calculated.

#### 3.5.6.a.5 Individual Pits:

Pit 13/53 (Fig. 3.91) differs from the other pits of the salt pan in that it has one unit only which consists of a moderate yellowish brown, poorly sorted, coarse to medium calcareous gypseous quartz arenite (Fig. 3.57). The sediments are loose and homogenous apart from the presence of small pockets of gypsum. There are two types of quartz (Fig. 3.57): the majority of grains are of medium to fine sand grade, subangular, subspherical and vitreous, the rest are of coarse sand grade, rounded, spherical and frosted. Gypsum is mainly present as coarse sand grade, with some gravel grade, anhedral grains which are cloudy (Fig. 3.57). Next in abundance are gypsum needles and rods, the finer sand grade needles are euhedral. A few discoidal crystals and cleavage plates are present. Carbonate grains are mainly present as peloids and pellets. Also present are coarse sand grade to gravel grade skeletal fragments, some of which are milky white. Green amphiboles and other heavy minerals are present in the fine sand grade.

Mineralogically the sediments consist of (Figs. 3.92 - 3.101): quartz (51%), gypsum (21%), aragonite (18%), calcite (7%) and dolomite (3%).

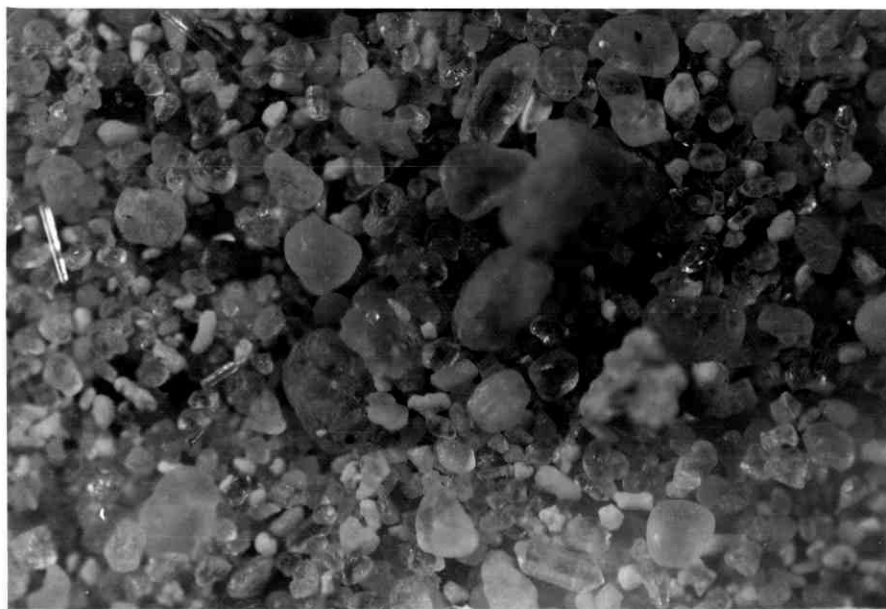


Fig. 3.57 Calcareous gypseous quartz arenite. Sample 386, pit 13/53.  
Note different habits of gypsum. Loose grains. X25.

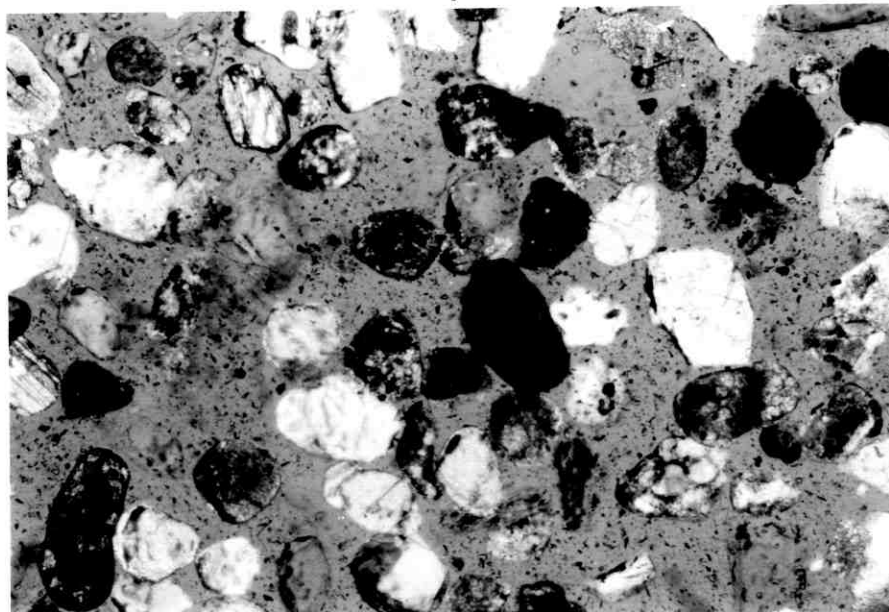


Fig. 3.58 Calcareous gypseous quartz arenite. Sample 296, pit 13/72.  
Gypsum grains were plucked out when thin section was made.  
Impregnated grains. Crossed nicols. X90.

At pit 13/47, (Fig. 3.91), Sub-unit b of the salt pan is overlaid by a middle and top calcarenite unit.

The middle unit is 200mm. thick and is composed of a pale yellowish brown, poorly sorted, coarse to fine quartzose gypseous calcarenite. The sediments are loose and layered, with a few lenses of shells. The carbonate grains are mainly fine to medium sand grade peloids some of which look similar to pellets. A few coarse sand grade to gravel grade shells and skeletal fragments are also present, some of which are milky white. Gypsum is mainly present as needles and rods, with the coarser sand grade crystals containing bubbles, some crystals are corroded. A very few cleavage plates and clear anhedral grains are present, together with some very short selenite habit crystals which look similar to discoids (and may in fact be a stage of formation of discoids). Quartz grains are generally coarse sand grade and spherical.

Mineralogically the sediments consist of (Figs. 3.92 - 3.102): aragonite (34.5%), gypsum (34.5%), quartz (21.5%), calcite (6.5%), dolomite (1.5%) and feldspars (1.5%).

The top unit is separated from the bottom unit by a 50mm. lens of gypsarenite which was sampled as part of the top unit. The sediments of the top unit consist of a moderate yellowish brown, moderately sorted, medium to fine quartzose gypseous pelletal calcarenite. The sediments are loose and laminated. Carbonate grains are mainly present as medium to fine sand grade pellets and round peloids, with a very few skeletal fragments. Gypsum is mainly present as coarse sand grade to gravel grade anhedral grains which are cloudy and contain inclusions. Next in abundance are discoids, some of which are clustered together. A very few gypsum needles are present. Quartz grains are of coarse to medium sand grade, spherical and rounded.

Mineralogically the sediments consist of (Figs. 3.92 - 3.101): aragonite (48.5%), gypsum (19%), quartz (16.5%), calcite (9.5%), dolomite (3%), feldspars (2.5%) and high-magnesium calcite (1%).

#### 3.5.6.b The Sediments at the South of the Salt Pan:

The four previously described sub-units a, b, c and d extend laterally towards the south of the pan (for photos of Sub-units c and d see Figs. 3.58 to 3.65), where the two bottom Sub-units a and



Fig. 3.59 Calcareous gypseous quartz arenite of Sub-unit d. Sample 450, pit 13/74. Loose grains. X25.

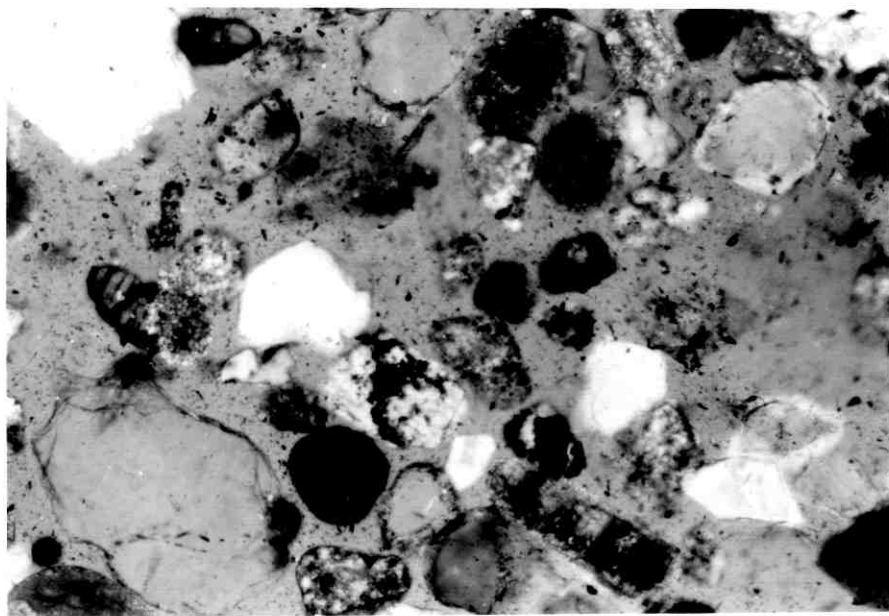


Fig. 3.60 Photomicrograph of impregnated grains of sample 450. (Gypsium grains were plucked out), Crossed nicols. X90.

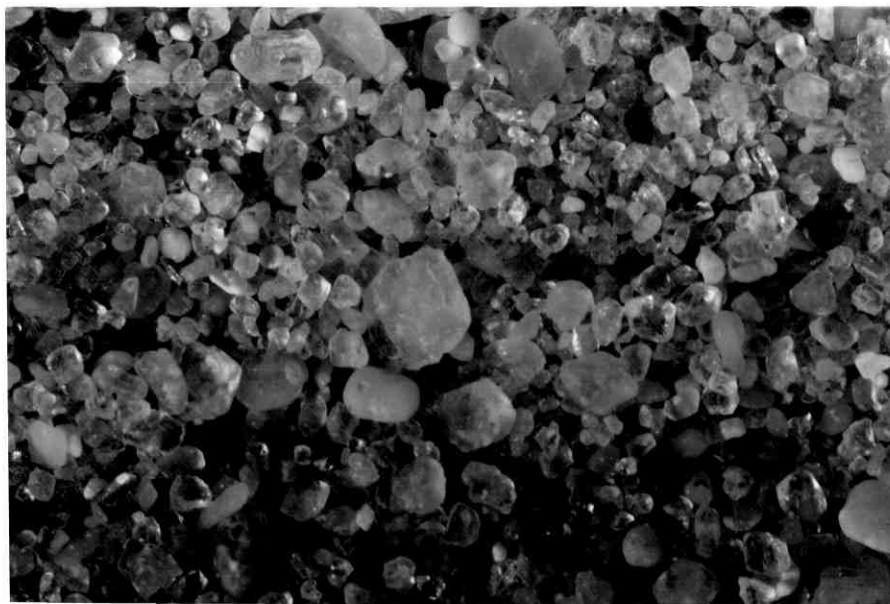


Fig. 3.61 Calcareous gypseous quartz arenite of Sub-unit d. Sample 463, pit 13/77. Loose grains. X25.

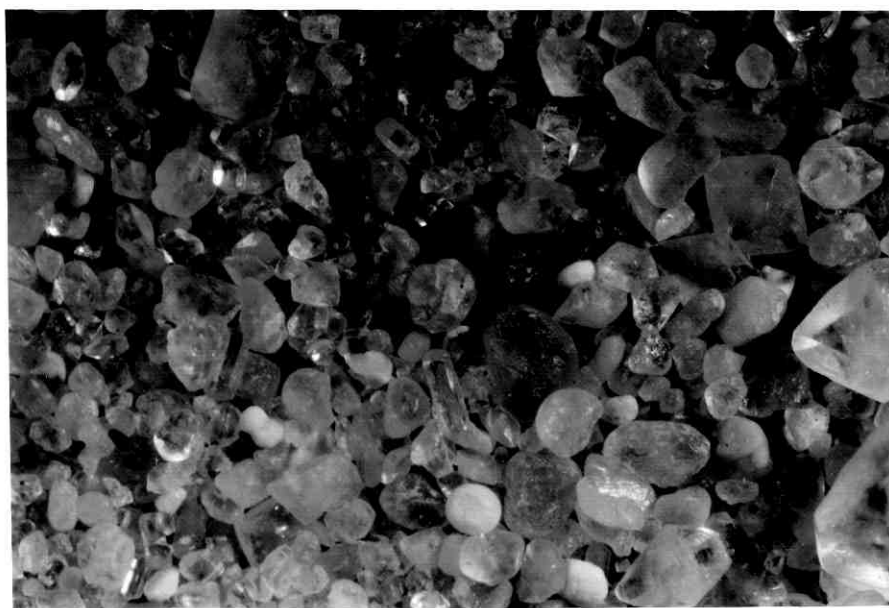


Fig. 3.62 Calcareous gypseous quartz arenite of Sub-unit d. Sample 466, pit 13/78. Note habits of gypsum.

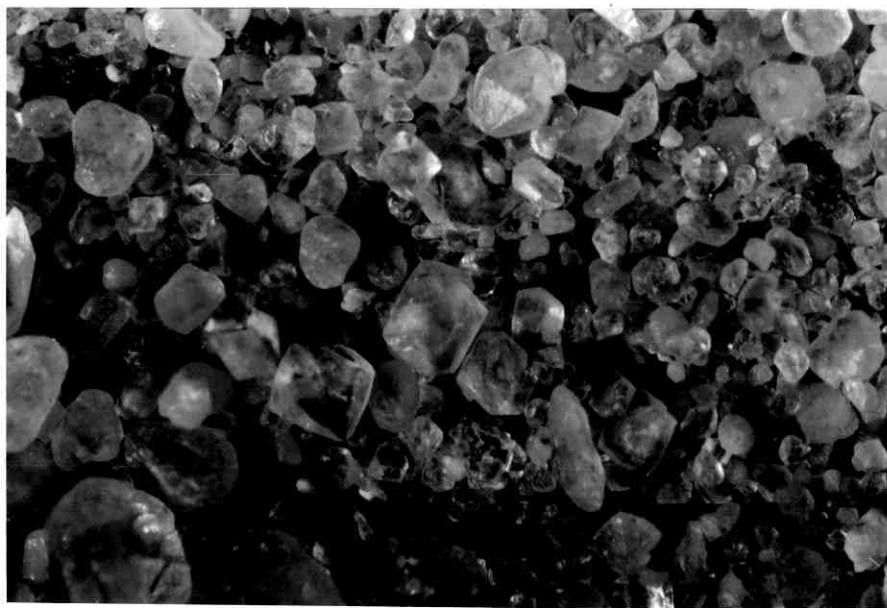


Fig. 3.63 Calcareous gypseous quartz arenite of Sub-unit d. Sample 470, pit 13/81. Note different habits of gypsum. Loose grains. X25.

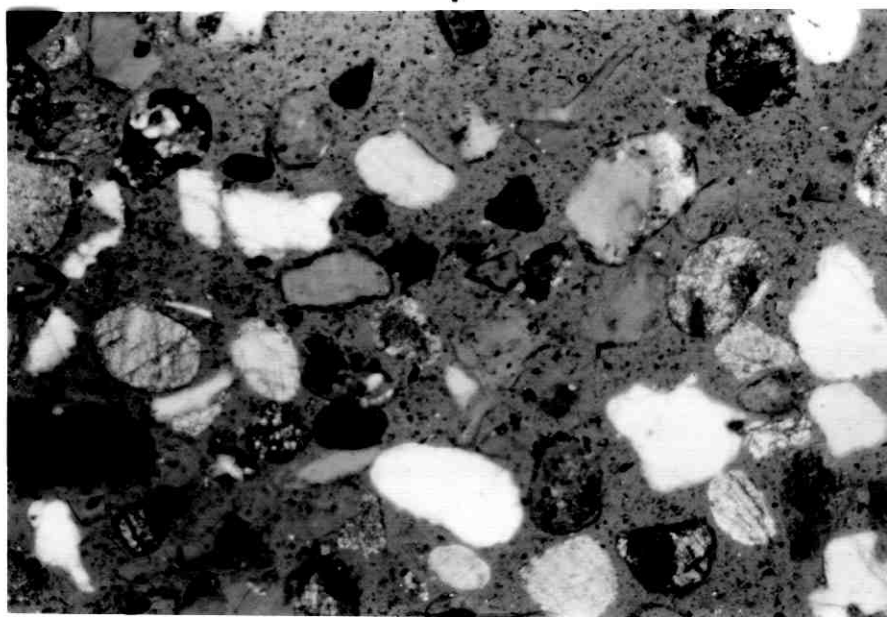


Fig. 3.64 Calcareous gypseous quartz arenite of Sub-unit c. Sample 297, pit 13/72. Gypsum grains are plucked out. Impregnated grains. Crossed nicols. X90.



Fig. 3.65 Calcareous gypseous quartz arenite of Sub-unit c. Sample 451, pit 13/74. Loose grains. X25.

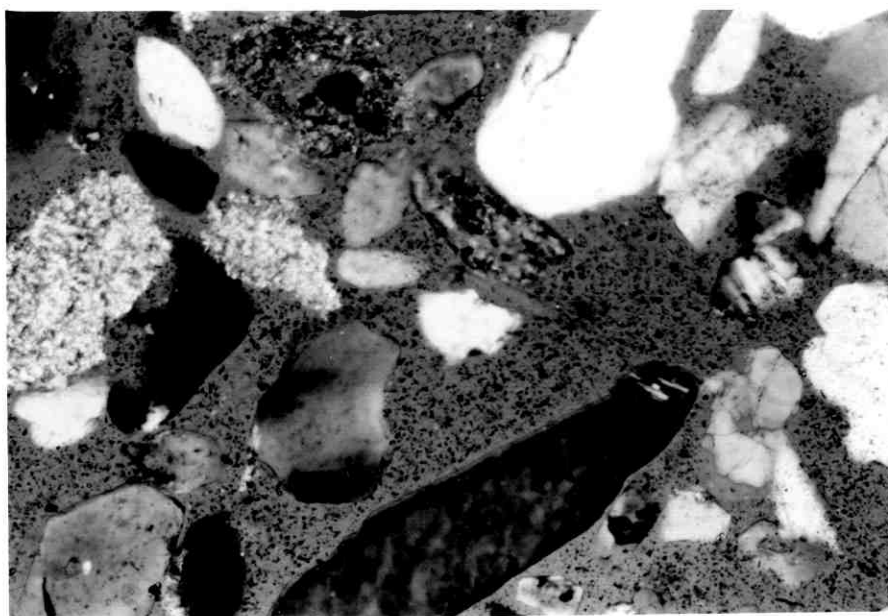


Fig. 3.66 Gypsum crystals and anhydrite nodules. Sample 299, pit 13/72. Impregnated grains. Crossed nicols. X90.

b grade into Sub-units a` and b`. At pit 13/77 and the following pits of profile VII - VIII, Sub-unit c is missing, and the sedimentary sequence consists of Sub-units a, b and d. The following is a description of the sediments of Sub-units a` and b`.

### 3.5.6.b.1 Sub-unit a`:

The sediments of this sub-unit consist of two layers but were sampled as one sub-unit; the lower layer consists of anhydrite and this grades into an anhydritic gypsarenite layer, so the following description is for a mixture of the two layers (in some pits the lower anhydrite layer was not reached and therefore gypsum appears more abundant than anhydrite e.g. sample 458, pit 13/75).

The sand grade sediments consist of light brownish gray, moderately sorted, coarse quartzose anhydritic gypsarenite. This unit occurs below the water-table, and its thickness is not known since its base was not reached. Gypsum is mainly present as coarse sand grade to gravel grade needles and rods (Figs. 3.66 - 3.78), which are generally corroded and contain bubbles (Figs. 3.69, 3.71, 3.72, 3.77 and 3.78). Sometimes an overgrowth may mis-shape some of the crystals (Fig. 3.71). Some of the gypsum needles are twinned (Fig. 3.70). Two types of needles are present: mainly those with six crystal faces parallel to the C-crystallographic axis, and the other type is with four crystal faces parallel to the C-crystallographic axis. A very few crystals are clear displacive discoids, and clear anhedral grains are also present (Fig. 3.69). Some of the gypsum crystals show corroded laths of anhydrite with a subparallel alignment (Figs. 3.68 and 3.70) suggesting that the gypsum crystals are after anhydrite (Shearman, 1978). Anhydrite nodules are generally coarse sand grade to gravel grade (Figs. 3.66, 3.67, 3.73, 3.74, 3.75 and 3.76), with the gravel grade nodules containing inclusions within them. Some of the coarse sand grade nodules appear to have a similar shape to the needles (Figs. 3.67 and 3.75) and discoids. Some gypsum needles appear to be being incorporated into or growing from the nodules (Fig. 3.76). Quartz grains are generally coarse to medium sand grade, rounded, sub-spherical and frosted. Carbonate grains are generally scarce and when present they are peloids.

Mineralogically the sediments consist of gypsum, anhydrite, calcite and feldspars having the following percentages (Figs. 3.92 - 3.101): gypsum (70 - 95%), anhydrite (0 - 25%), quartz (4 - 14%), calcite

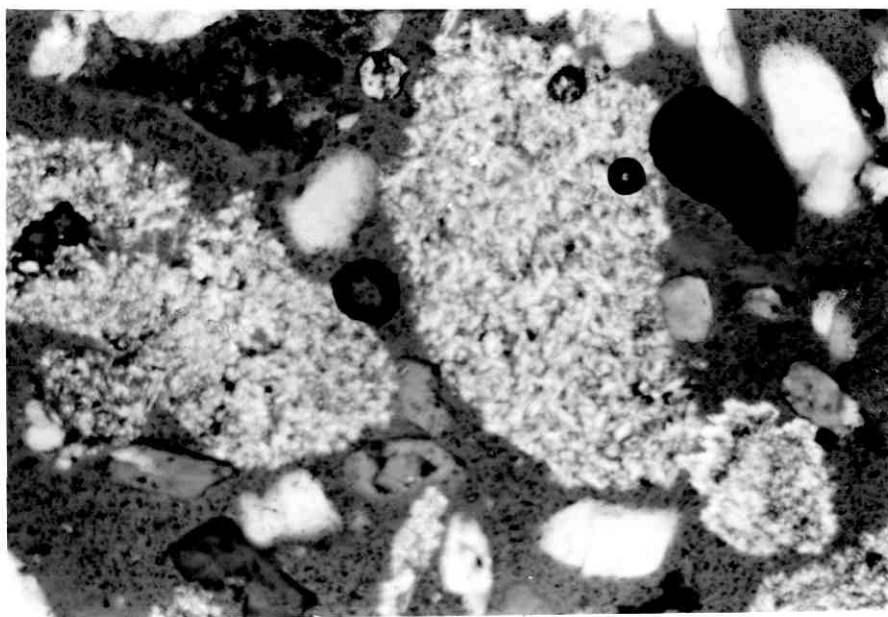


Fig. 3.67 Anhydrite nodules. Sample 299, pit 13/72. Impregnated grains. Crossed nicols. X90.

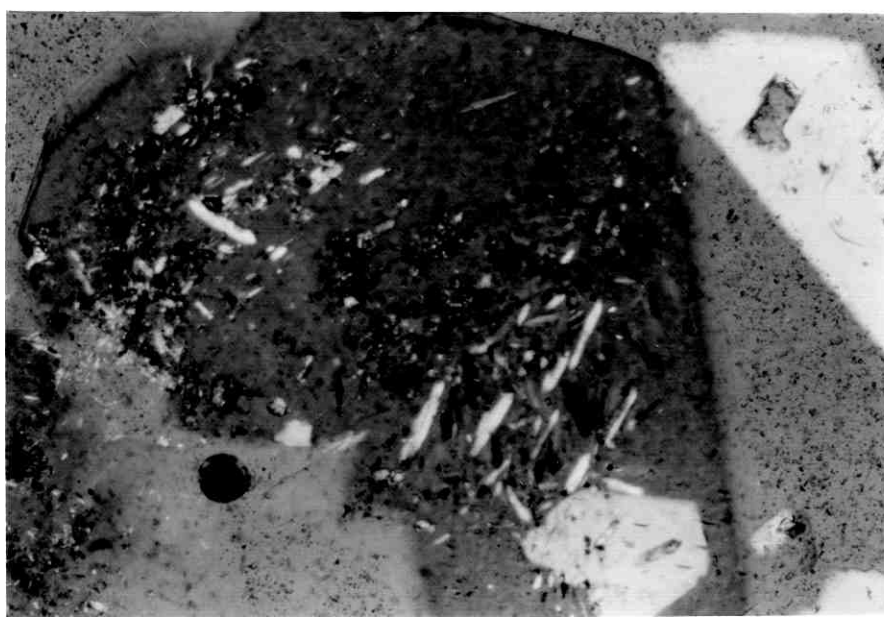


Fig. 3.68 Gypsum crystal with corroded anhydrite laths. Sample 453, pit 13/74. Note sub-parallel alignment of laths. Impregnated grains. Crossed nicols. X90.



Fig. 3.69 Gypsarenite. Gypsum needles and anhedral gypsum grains. Sample 453, pit 13/74. Loose grains. X25.

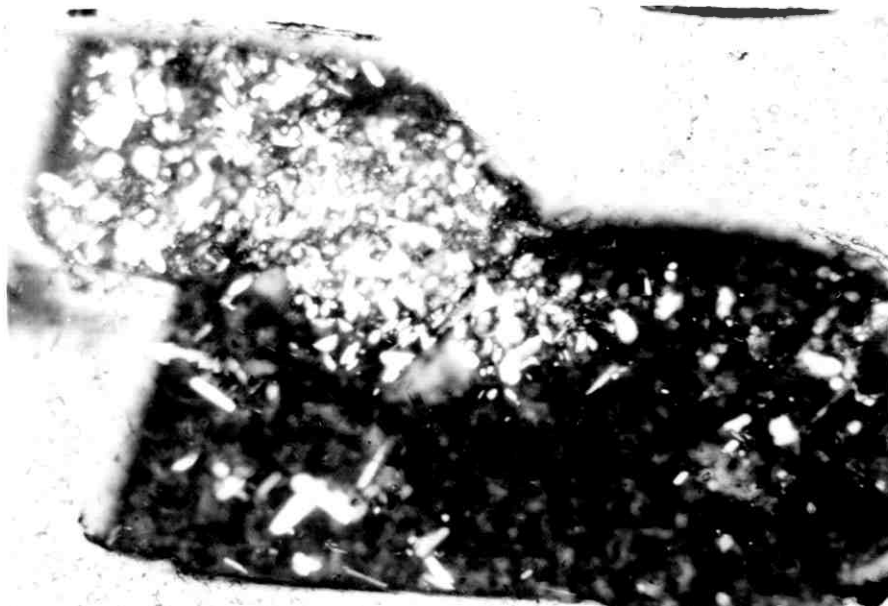


Fig. 3.70 Gypsum crystals with anhydrite lathes. Sample 458, pit 13/75. Impregnated grains. Crossed nicols. X144.



Fig. 3.71 Gypsarenite. Corroded gypsum needles. Sample 461, pit 13/76. Loose grains. X25.



Fig. 3.72 Corroded gypsum crystals. Sample 465, pit 13/77. Impregnated grains. Crossed nicols. X144.

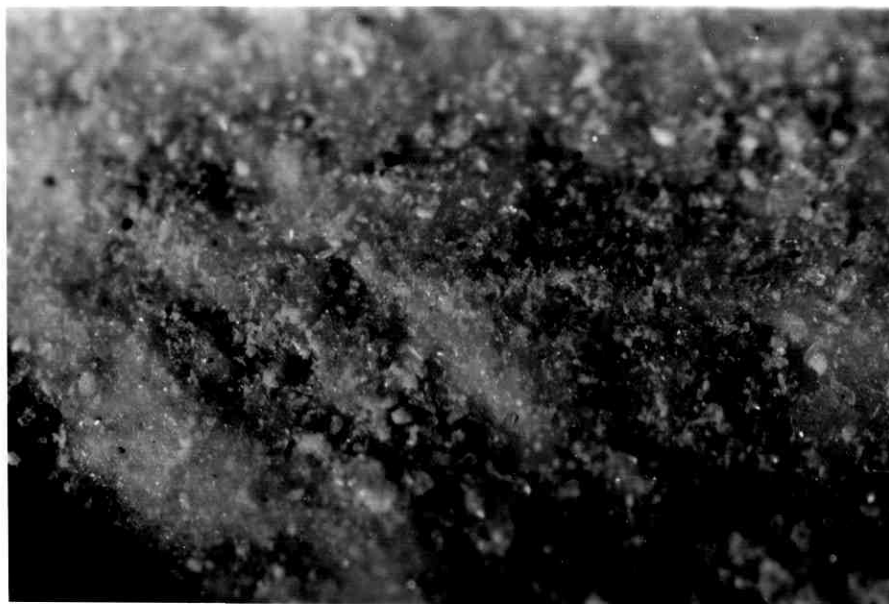


Fig. 3.73 Surface of gravel grade anhydrite nodule. Sample 465, pit 13/77. Loose grains. X25.

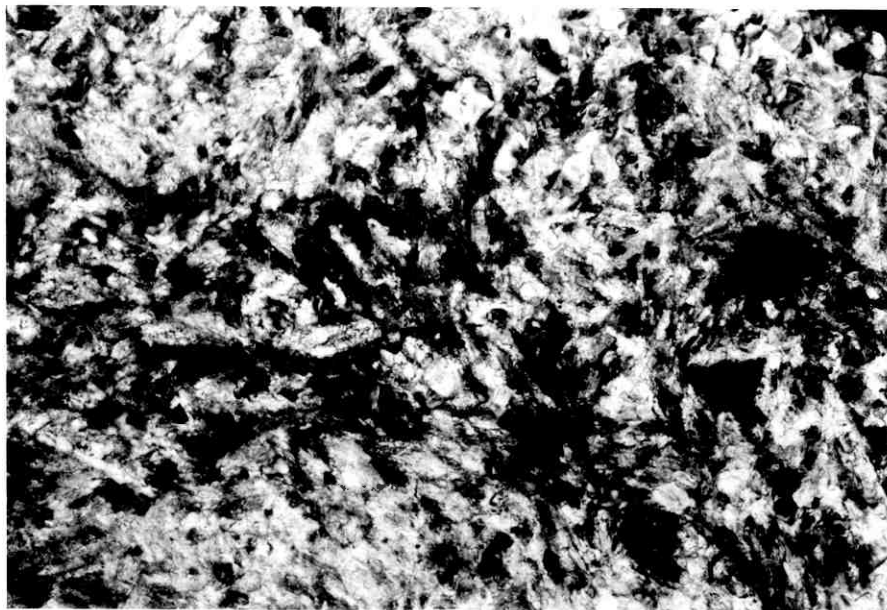


Fig. 3.74 Photomicrograph of anhydrite nodule. Sample 465, pit 13/77. Impregnated grains. Crossed nicols. X144.

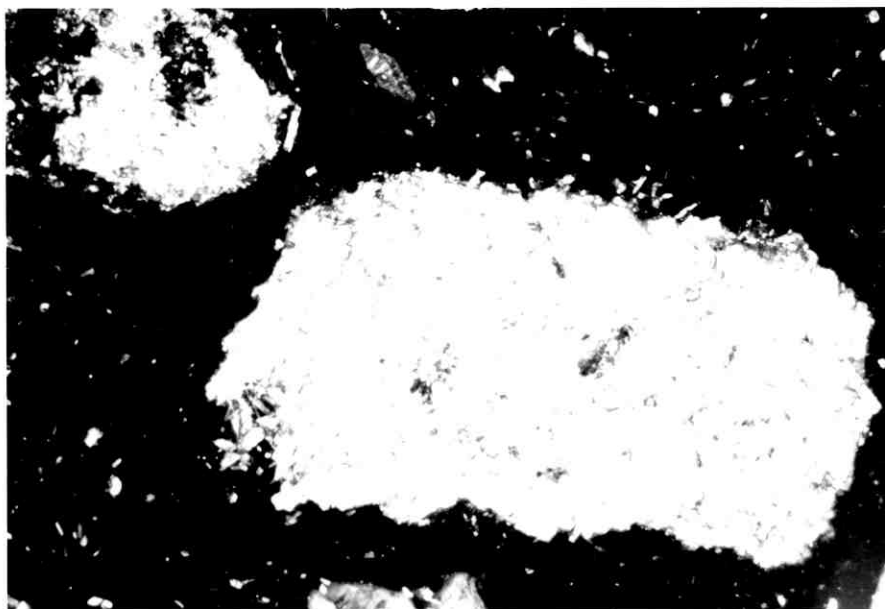


Fig. 3.75 Photomicrograph of anhydrite nodules. Sample 465, pit 13/77. Impregnated grains. Crossed nicols. X144.

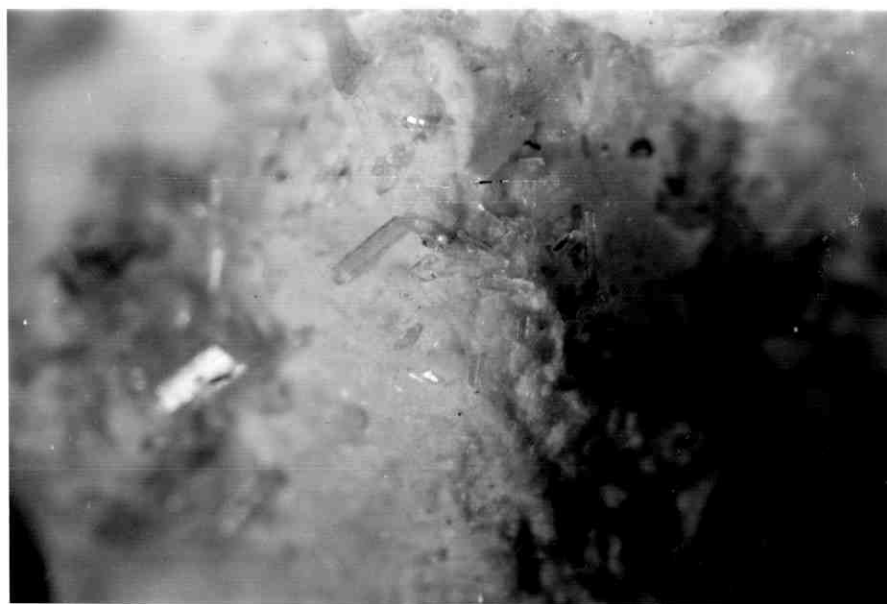


Fig. 3.76 Surface of anhydrite nodule. Sample 468, pit 13/78. Note some gypsum needles appear to be incorporated in or growing from nodule. Loose grain. X25.



Fig. 3.77 Gypsarenite. Corroded gypsum needles. Sample 472, pit 13/81. Loose grains. X25.

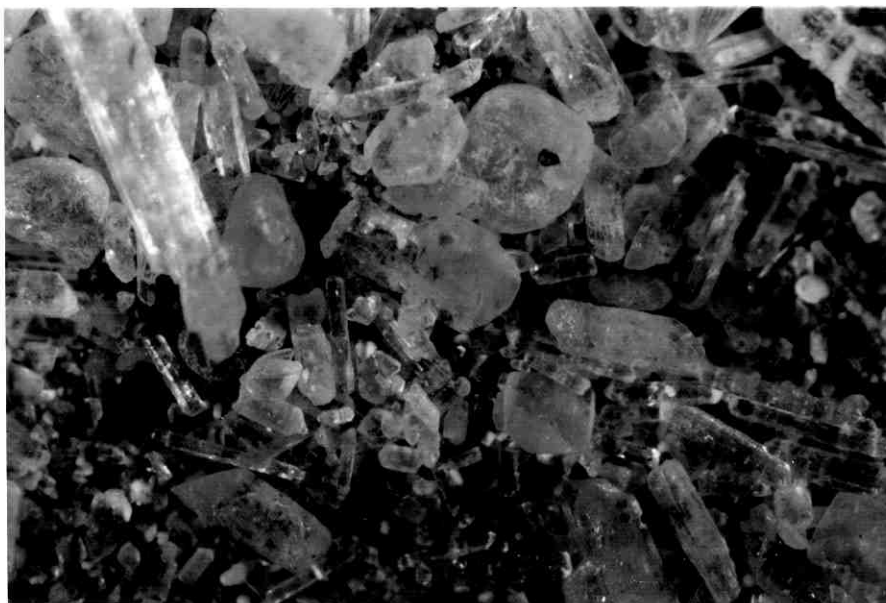


Fig. 3.78 Gypsarenite. Note corroded needles and different habits of gypsum. Sample 473, pit 13/83. Loose grains. X25.

(0 - 7%) and feldspars (2 - 5%).

#### 3.5.6.b.2 Sub-unit b:

This unit is capped by a 30mm. layer of anhydrite in pits 13/72, 13/74, 13/75 and 13/76. This anhydrite layer is absent in pits 13/77, 13/78 and 13/81. The sediments of Sub-unit b grade from a very pale brownish orange (with white nodules), poorly sorted, medium anhydritic gypseous quartz arenite (pit 13/72) to a white, poorly sorted, anhydrite ruditic coarse quartzose anhydrite arenite (pits 13/74, 13/75 and 13/76) to a yellowish gray, moderately sorted, gypsum ruditic, coarse gypsarenite (pits 13/77, 13/78, 13/81 and 13/83). Quartz grains are mainly medium to fine sand grade with a few coarse grains, similar to those of Unit 2. Gypsum grains are of different habits; at pit 13/72 gypsum is mainly present as very coarse anhedral grains, some of which contain inclusions, with a few discoids and a very few needles. At pits 13/74, 13/75 and 13/76 gypsum is small in amount and mainly present as corroded needles. At pits 13/77 and 13/78, gypsum is present as gravel grade to coarse sand grade needles and rods which are corroded and contain bubbles (Figs. 3.80, 3.81 and 3.82) and an overgrowth tends to mis-shape some of the coarse sand grade crystals. There are also small, selenite habit, crystals, and even smaller types which appear like a stage of transformation into discoids. At pit 13/81, the sediments contain gypsum which is present as very coarse sand grade and gravel grade cloudy discoidal gypsum which do not contain inclusions and some crystals have an overgrowth which tends to mis-shape them (Figs. 3.83 and 3.84). Anhydrite is only present in the sediments of pits 13/72, 13/74, 13/75 and 13/76. It is present as gravel grade to coarse sand grade nodules (Fig. 3.79) which sometimes contain inclusions. At pit 13/72 anhydrite nodules have a similar shape to the gypsum grains and discoids present in the sediments, thus suggesting that some of the gypsum present may have dehydrated.

#### 3.5.6.c. Pit 13/82, South of the Pan:

Further to the south of the pan, at pit 13/82, two sedimentary units are present, these are Sub-unit b overlaid by Sub-unit d, but the gypsum in the sediments of Sub-unit d is mainly present as gypsum needles and rods with very few of the short, selenite habit, crystals.

#### 3.5.6.d The polygonal Patterned Ground, West of the Salt Pan:

At pit 13/70, the polygonal patterned ground the surface sediments



Fig. 3.79 Anhydrite nodules and quartz grains. Sample 452, pit 13/74. Loose grains. X25.

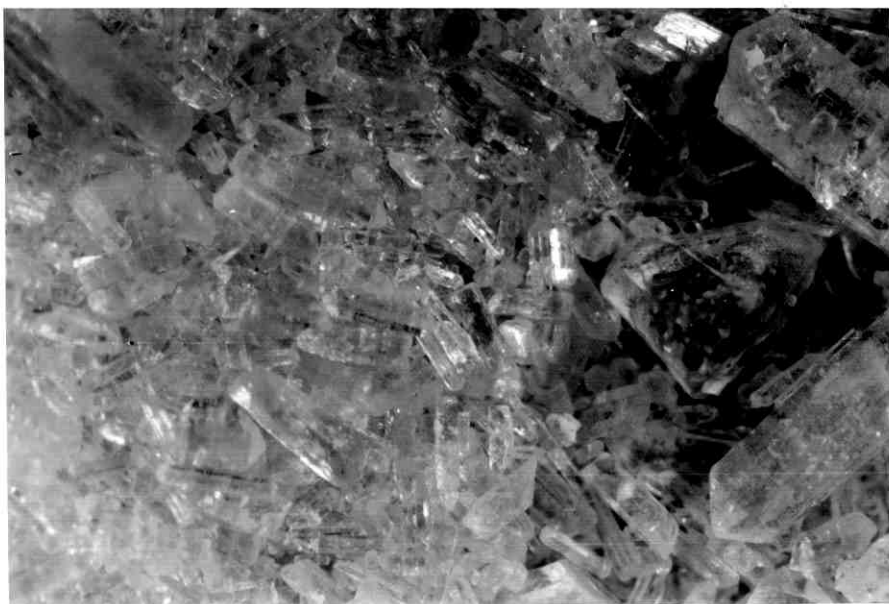


Fig. 3.80 Gypsum needles. Sample 464, pit 13/77. Loose grains. X25

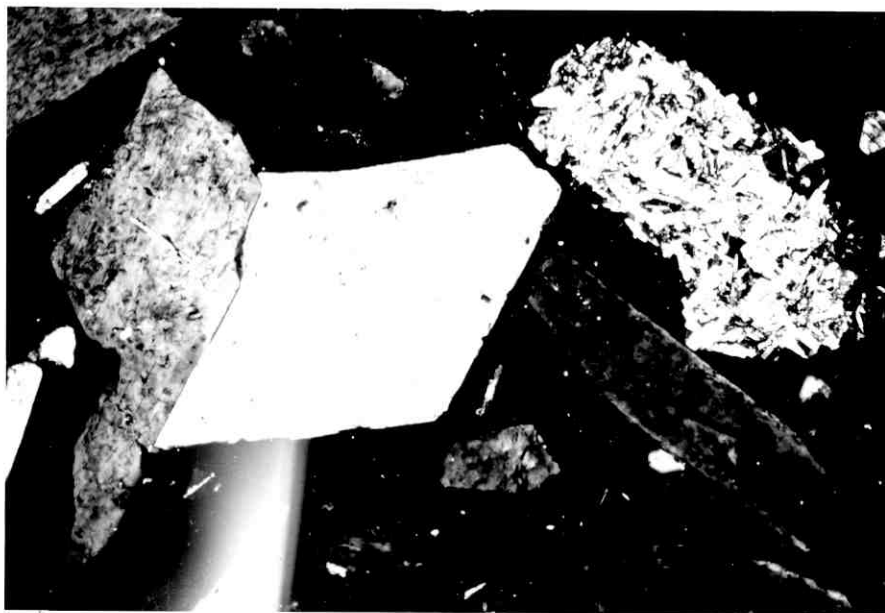


Fig. 3.81 Twinned gypsum crystal and needles. Sample 467, pit 13/78.  
Impregnated grains. Crossed nicols. X90.



Fig. 3.82 Gypsarenite. Gypsum needles. Sample 467, pit 13/78.  
Loose grains. X25.



Fig. 3.83 Discoidal gypsum with overgrowth. Sample 471, pit 13/81.  
Loose grains. X25.



Fig. 3.84 Discoidal gypsum with overgrowth. Sample 472, pit 13/81.  
Impregnated grains. Crossed nicols. X90.

may be divided into two units: a calcarenite layer overlaid by a quartz arenite layer.

The calcarenite layer consists of a grayish orange, poorly sorted, very coarse to medium gypseous quartzose calcarenite. The unit is weakly cemented with gypsum and contains 2% silt plus clay grade material. The carbonate grains are mainly very coarse sand grade skeletal fragments which are worn (Fig. 3.86 and 3.87). Peloids are also common (Figs. 3.86 and 3.88). Quartz grains are mainly of a coarse to medium sand grade, frosted, rounded, spherical with some grains having a slight carbonate coating. Gypsum is mainly present as cement poikilotopically enclosing the host carbonate grains (Figs. 3.86 and 3.87) and anhedral grains and very few discoids some of which are broken. Heavy minerals are present in the fine sand grade in a small amount.

Mineralogically the sediments consist of (Figs. 3.92 - 3.101): carbonate minerals (56%); (aragonite (48%), calcite (6.5%) and dolomite (1.5%)), quartz (32%), gypsum (10%) and feldspars (3%).

The quartz arenite layer is loose, homogenous and contains 12% silt plus clay grade material. It consists of a pale yellowish brown, poorly sorted, medium to fine calcilutitic gypseous calcareous quartz arenite. Quartz grains are of two types: mainly medium to fine sand grade, with a few coarse sand grade grains (Fig. 3.85). Carbonate grains are mainly of coarse sand grade, with few gravel grade, skeletal fragments and peloids (Fig. 3.85). Gypsum is mainly present as cloudy poikilotopic, worn discoidal crystals and a few anhedral grains (Fig. 3.85). Magnetite and other heavy minerals are present in the fine sand grade.

Mineralogically the sediments consist of (Figs. 3.92 - 3.101): quartz (62%), aragonite (15%), calcite (13%), dolomite (3%), feldspars (3%), gypsum (2.5%) and anhydrite (1.5%). The amount of carbonate minerals present in the sand grade is less than is suggested by the mineralogical analysis, so they must also be present in the silt plus clay grade material.



Fig. 3.85 Gypseous calcarous quartz arenite. Sample 291, pit 13/70.  
Loose grains. X25.

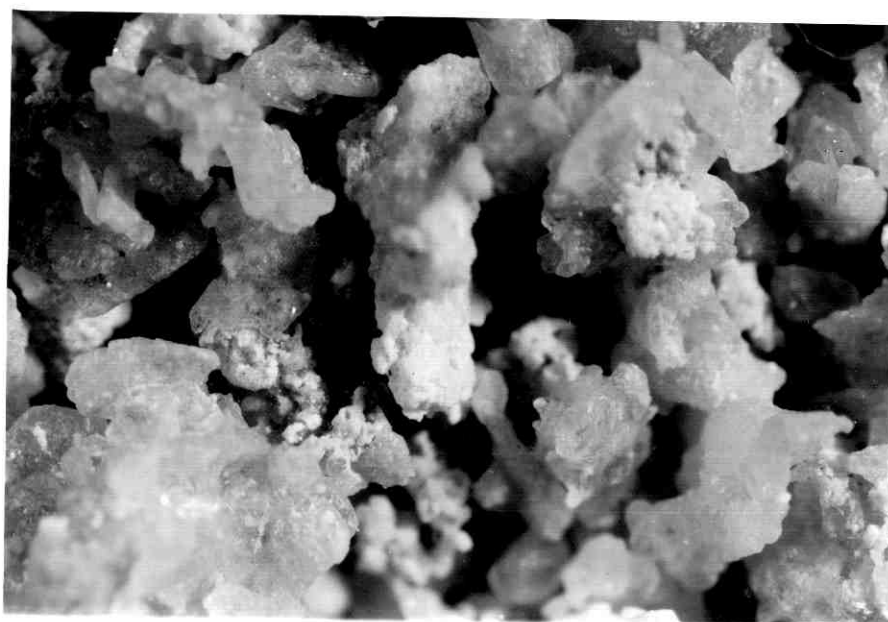


Fig. 3.86 Carbonate grains and poikilotopic gypsum cement. Sample  
292, pit 13/70. Loose grains. X25.

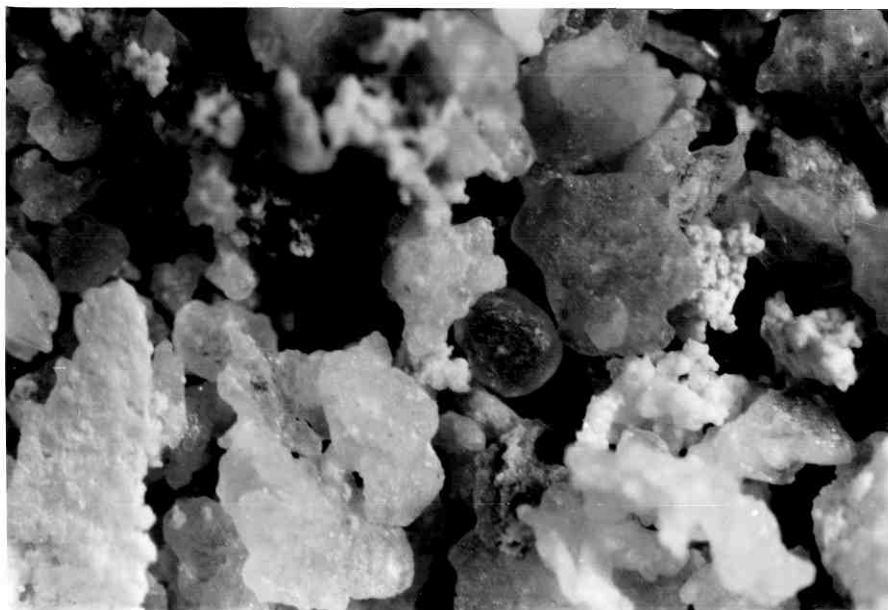


Fig. 3.87 Carbonate grains and poikilotopic gypsum cement. Sample 292, pit 13/70. Loose grains. X25.

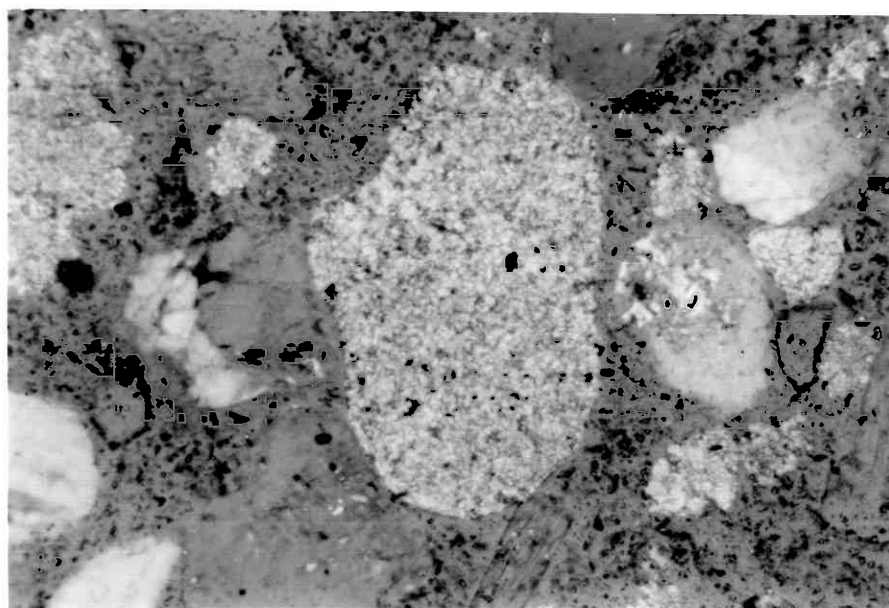


Fig. 3.88 Micritized peloid. Sample 292, pit 13/70. Impregnated grains. Crossed nicols. X144.

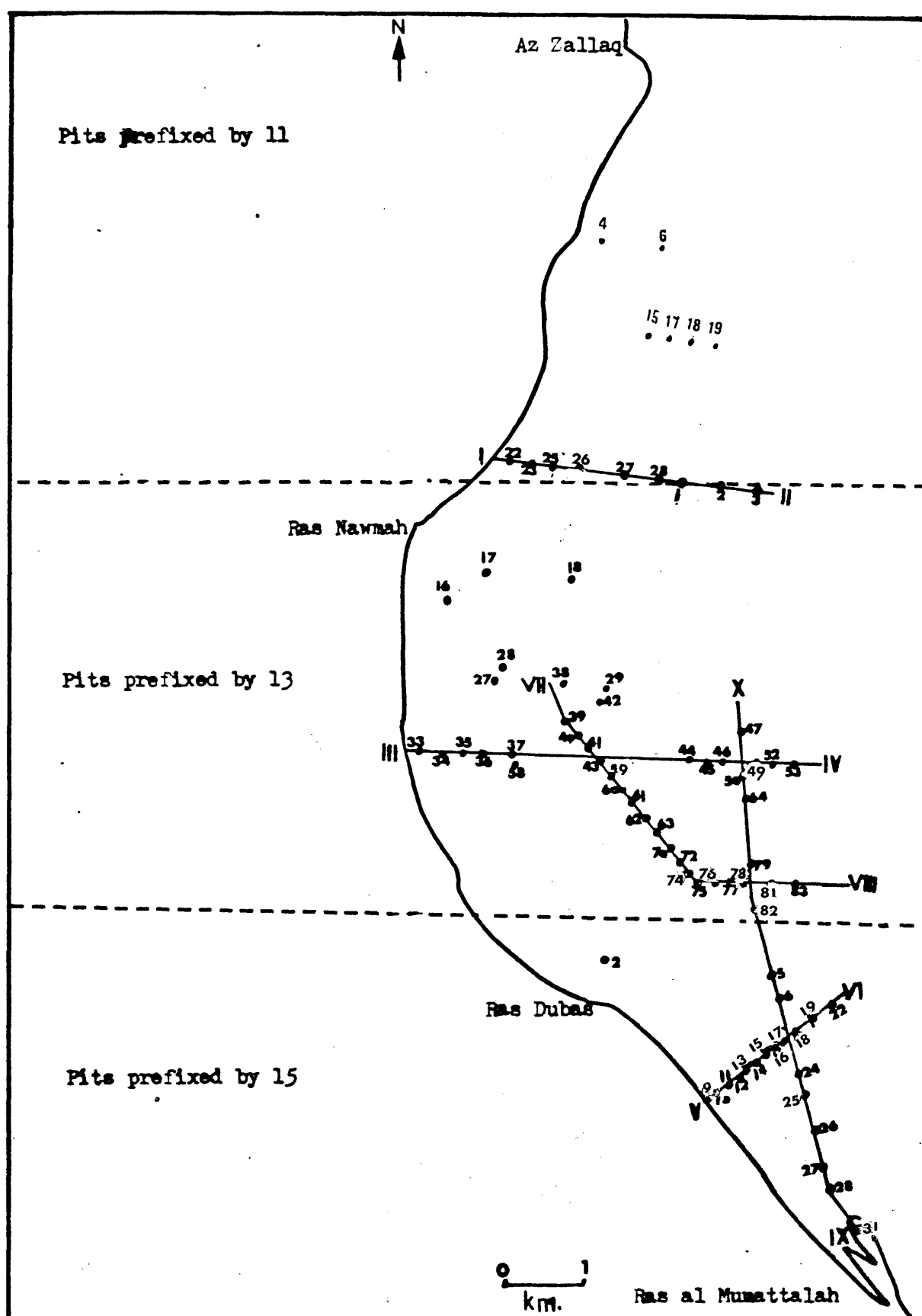


Fig. 3.39 Locations of profiles and pits in the area of study (prefix depends on number of 1:10,000 map, published by B.S.M.R.S., 1979).

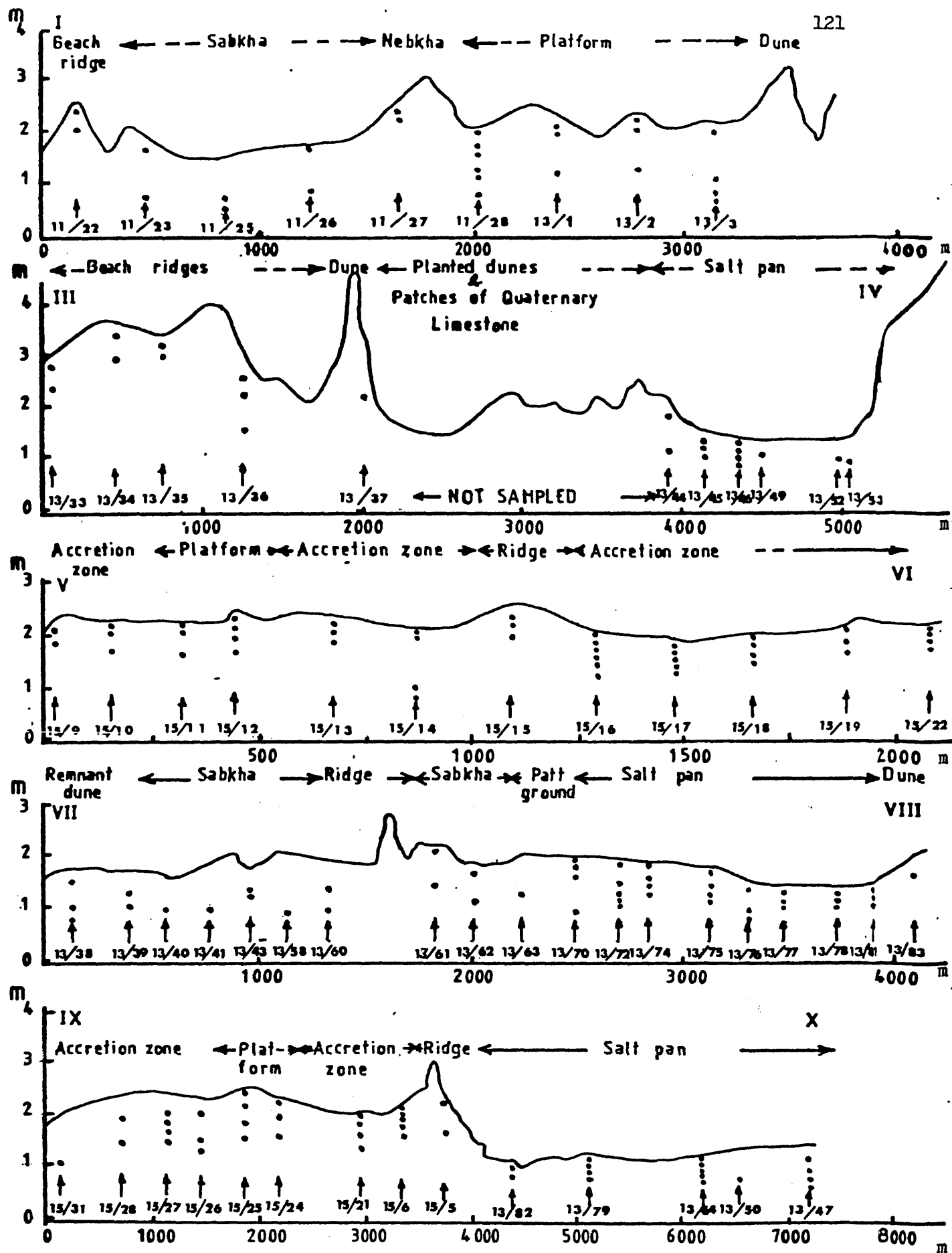


Fig. 3.90 Profiles, pits and position of samples in each pit (for sample numbers see Table 3.1).

11/22	11/23	11/25	11/26	11/27	11/28	11/29	11/30	12/1	12/2	12/3
1073	1075	1076	1082	1083	1093	1096	NS	1106		
1074	1075	1078	1081	1084	1092	1097	1101	1105		
1077		1077		1085	1091	1096	NS	1104		
					1090	1095	1100	1103		
					1089	1094	1098	0		
					1088					

13/33	13/34	13/35	13/36	13/37		13/44	13/45	13/46	13/49	13/52	13/53
1148	1151	1154	1158	1110	NOT SAMPLED	369	373	381	NS	NS	386
1149	1150	1153	1157			370	374	380	384	NS	
			1156				375	378	NS	NS	
			1155					379	NS	385	

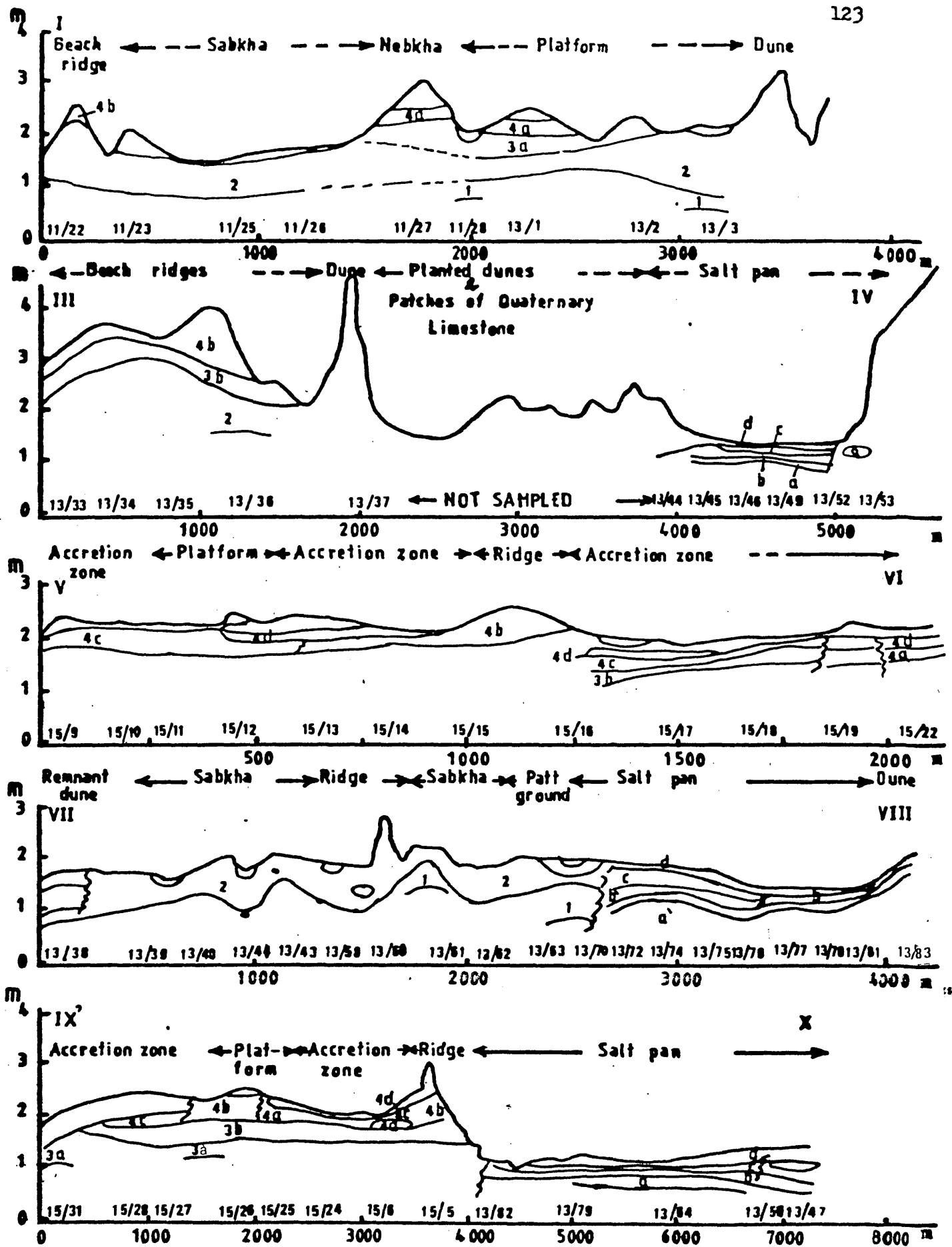
15/9	15/10	15/11	15/12	15/13	15/14	15/15	15/16	15/17	15/18	15/19	15/22
251	256	260	265	394	474	397	478	400	406	486	414
252	257	261	266	395	475	399	479	401	407	487	410
	258	263	267	396	476	398	480	402	408	488	411
			268		477		481	403	409	489	412
			NS				482	404			413
							483				
							484				

13/38	13/39	13/40	13/41	13/43	13/58	13/60	13/61	13/62	13/63	13/70	13/72	13/74	13/75	13/76	13/77	13/78	13/81	13/83
1125	NS	359	NS	355	NS	350	281	286	288	291	296	450	455	459	463	466	470	NS
1124	364		358		353	352	282	285		292	297	451	456	460	464	467	471	NS
1123	362									293	298	452	457	NS	465	468	472	473
										294	NS	453	458	461				
										299		NS						

15/31	15/28	15/27	15/26	15/25	15/24	15/6	15/5	13/82	13/79	13/84	13/50	13/47
NS	NS	804	NS	801	NS	673	NS	683	686	691	NS	812
NS	045	805	042	802	NS	674	680	684	687	692	NS	813
048	046	806	043	803	039	676	681		688	693	NS	814
		807	044		040	677			689	694	696	
			NS									

13/58	13/28	13/27	13/29	13/42	13/18	13/17	13/16	13/2
1113	1116	1119	1128	1131	1136	1138	1141	388
		1120		1130				387
								386

Table 3.1. Pit and sample numbers. For locations see Fig. 3.90. (NS means not sampled and 1077 means sample missing).



Figs. 3.91 Cross-sections of southwest sabkha, showing sedimentary units.

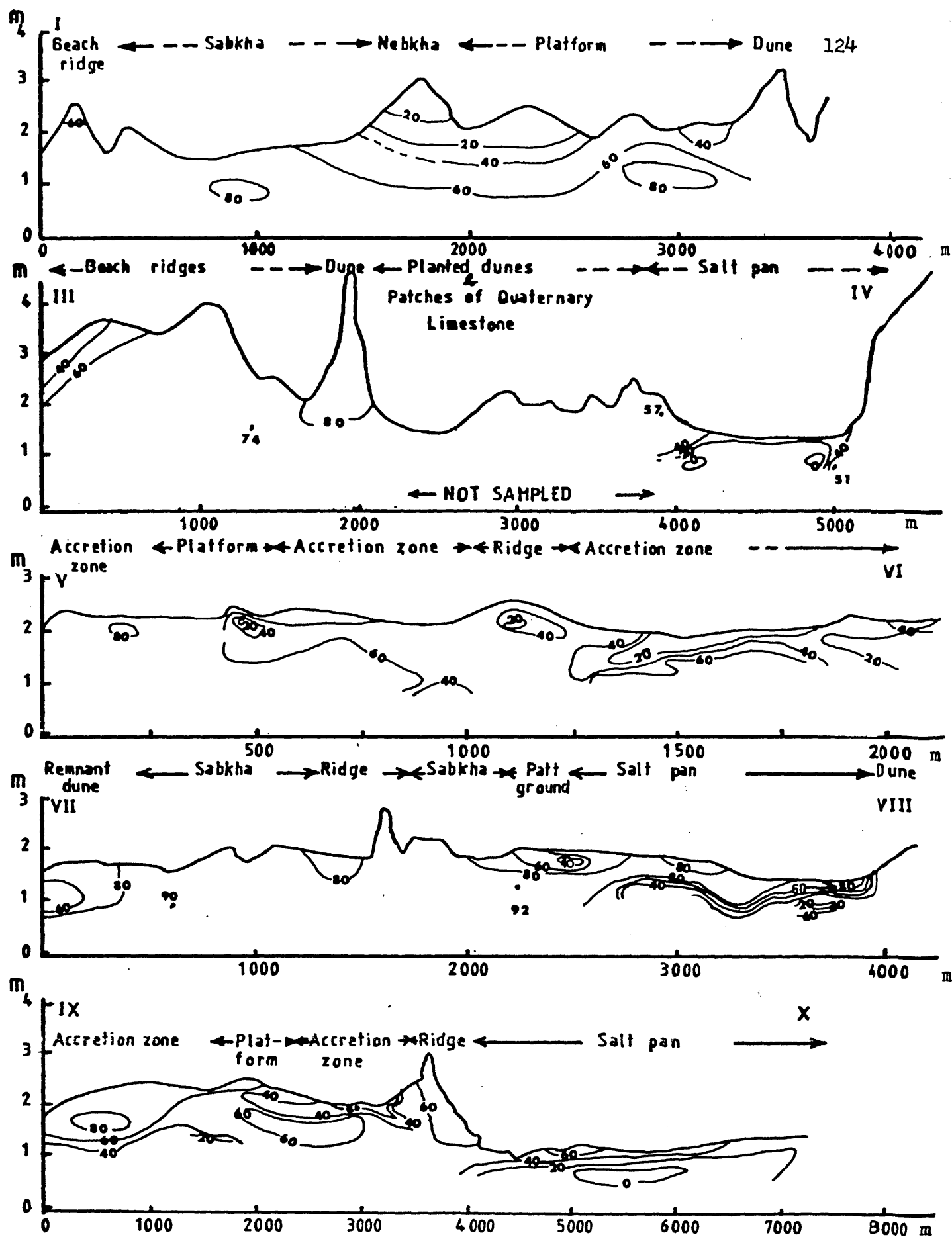


Fig. 3.92 The distribution and percentage of quartz in the sediments. Contour interval (C.I.) = 20.

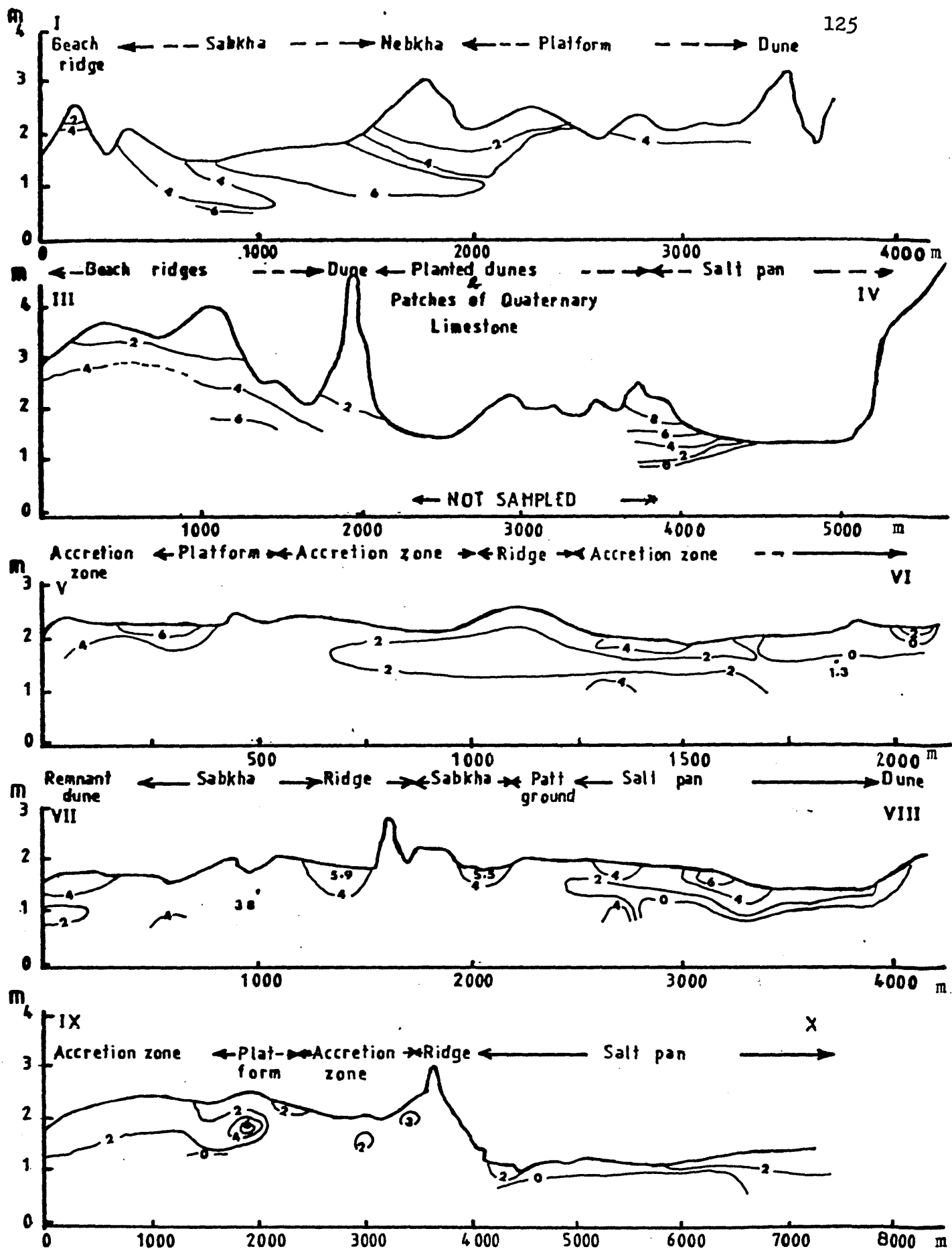


Fig. 3.93 The distribution and percentage of feldspars in the sediments.  
C.I. = 2 .

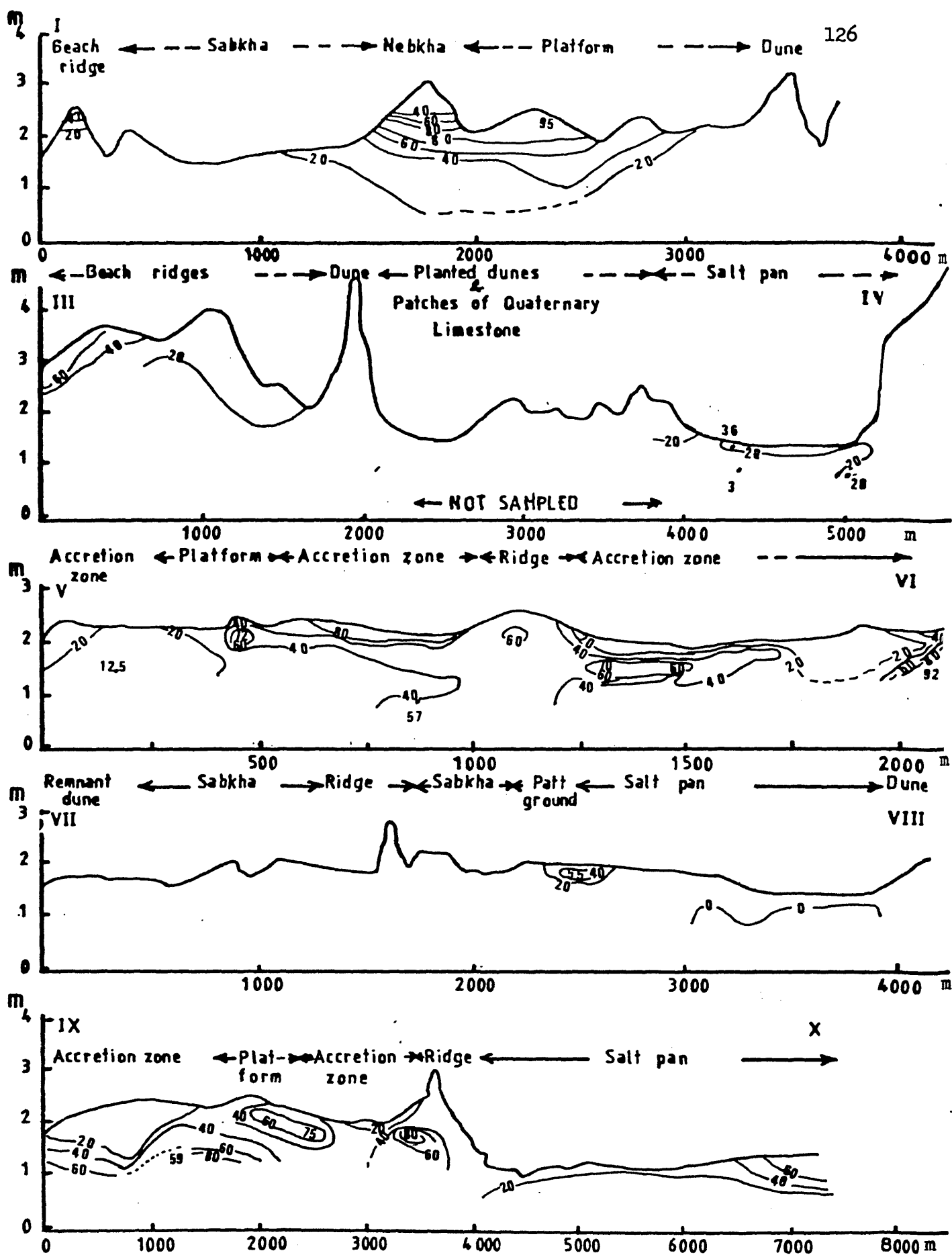


Fig. 3.94 The distribution and percentage of carbonate minerals in the sediments. C.I. = 20.

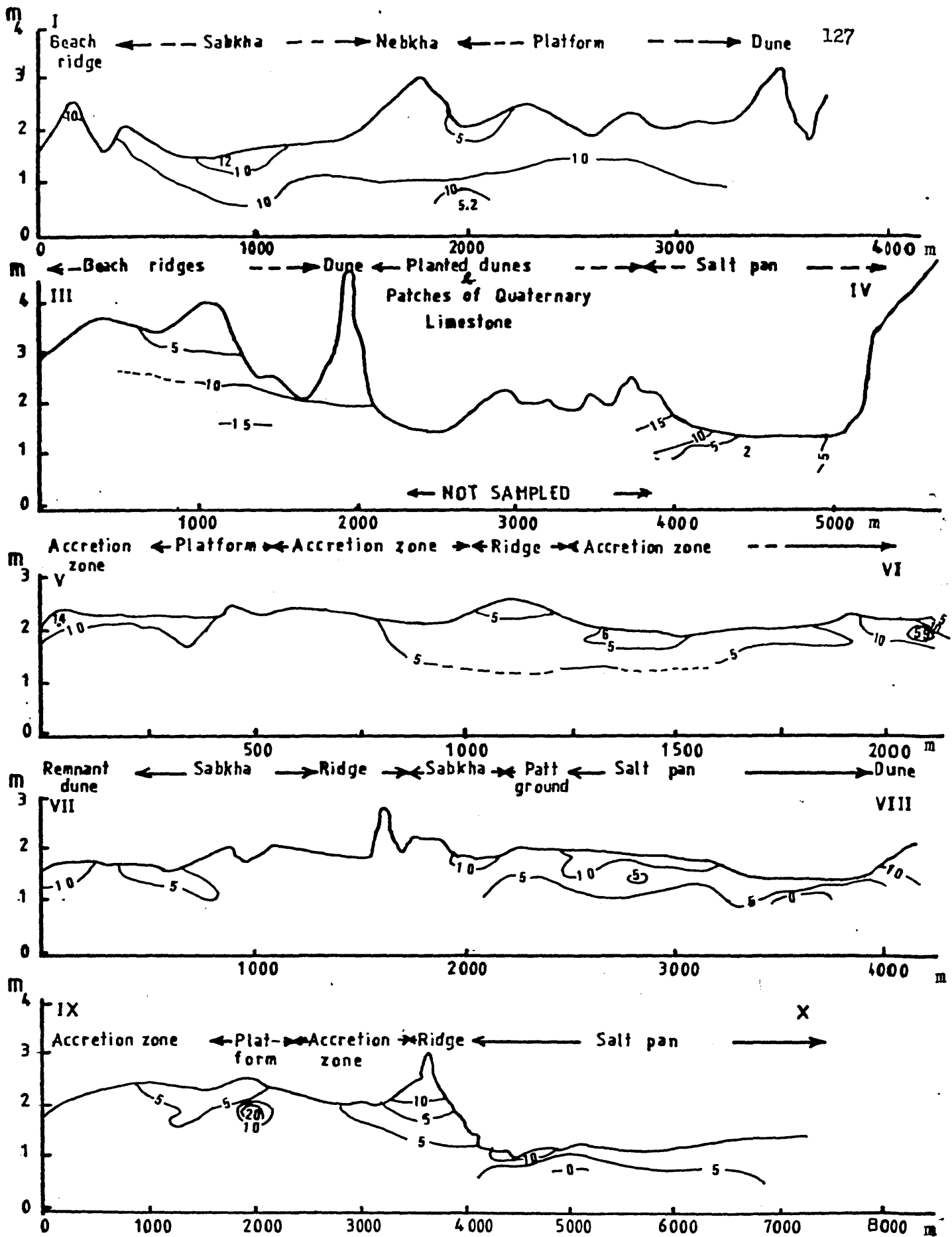


Fig. 3.95 The distribution and percentage of calcite in the sediments.  
C.I. = 5.

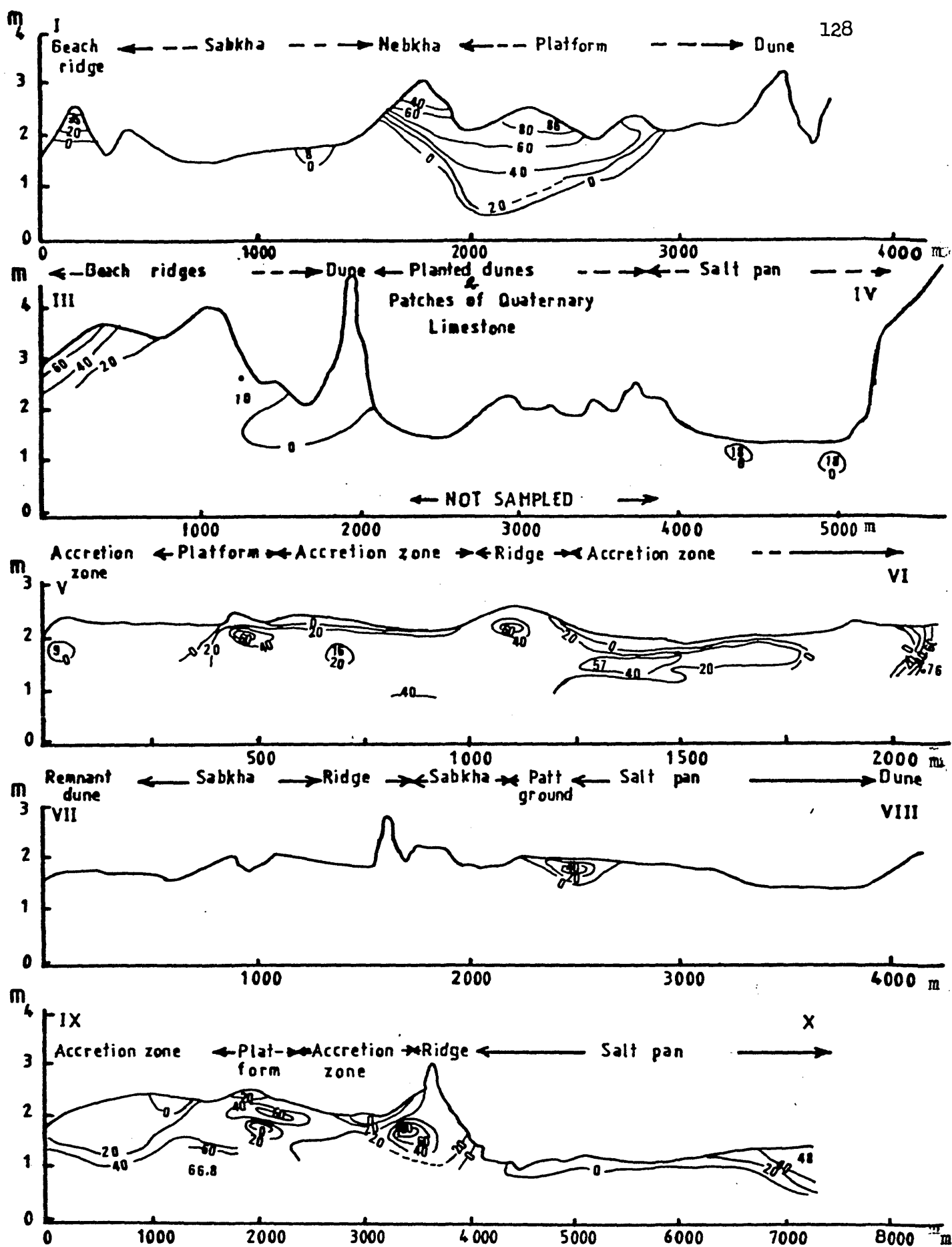


Fig. 3.96 The distribution and percentage of aragonite in the sediments.  
C.I. = 5.

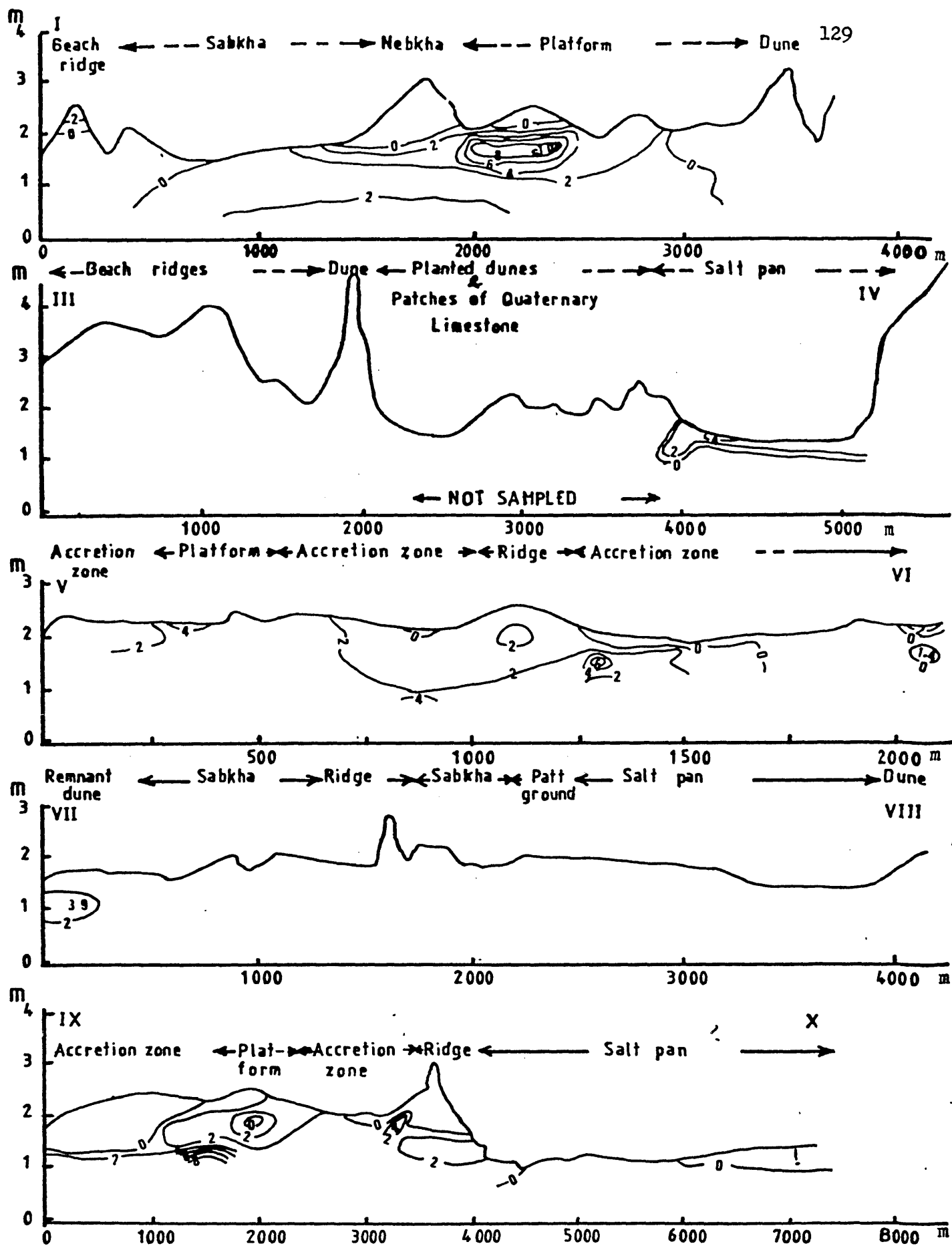


Fig. 3.97 The distribution and percentage of high-magnesium calcite in the sediments. C.I. = 2.

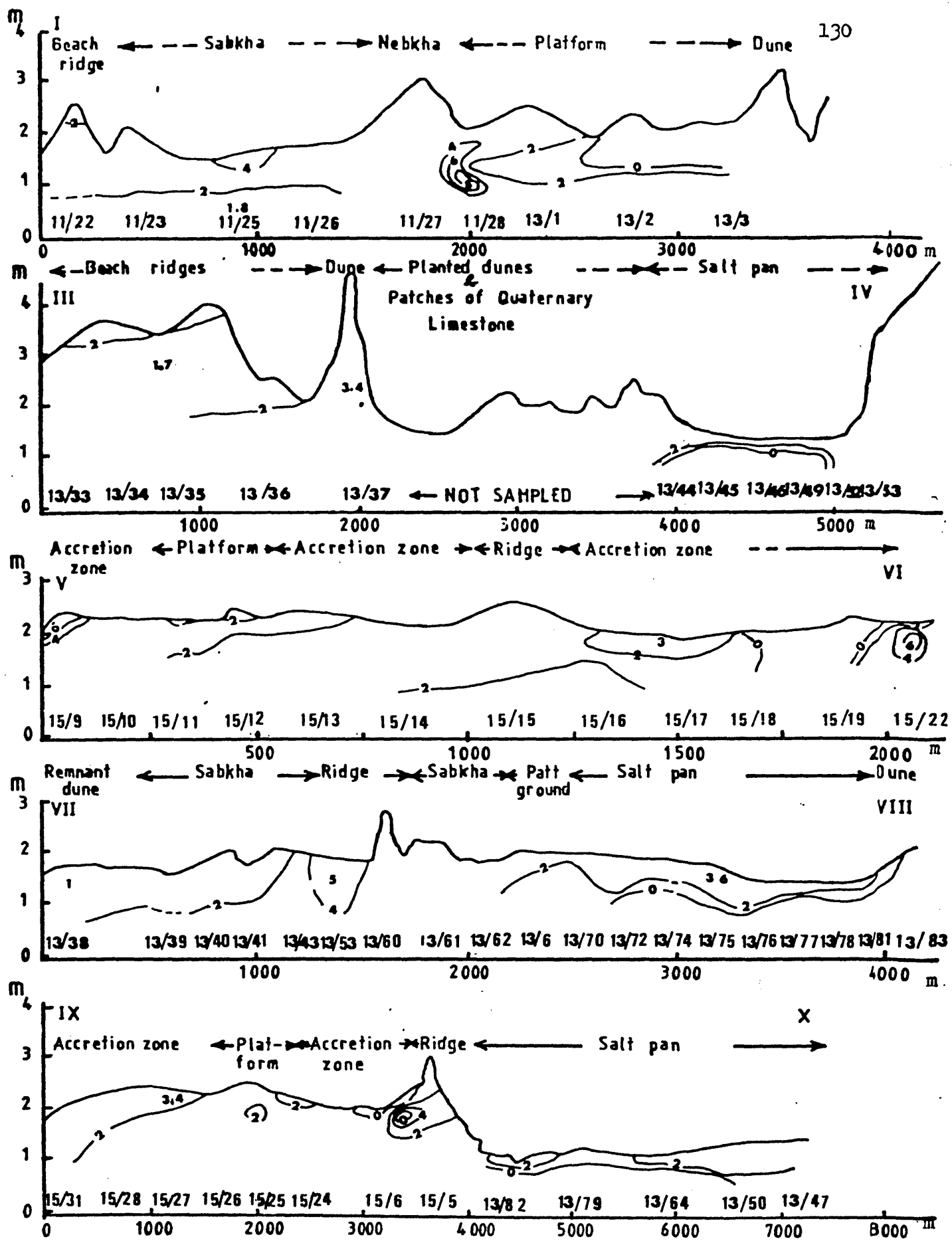


Fig. 3.98 The distribution and percentage of dolomite in the sediments, G.I. = 2.

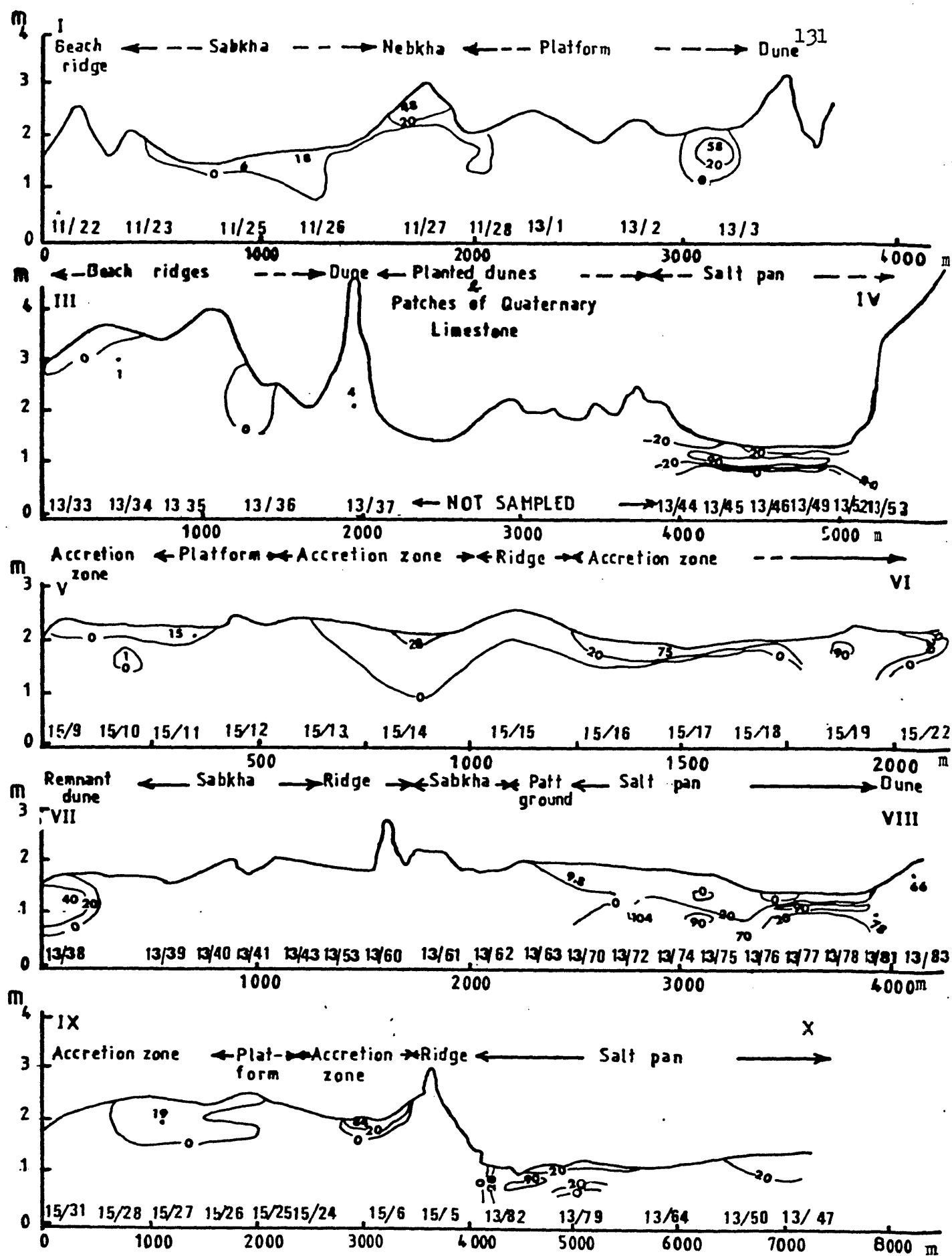


Fig. 3.99 The distribution and percentage of gypsum in the sediments. Contours at 0, 20 and 90%.

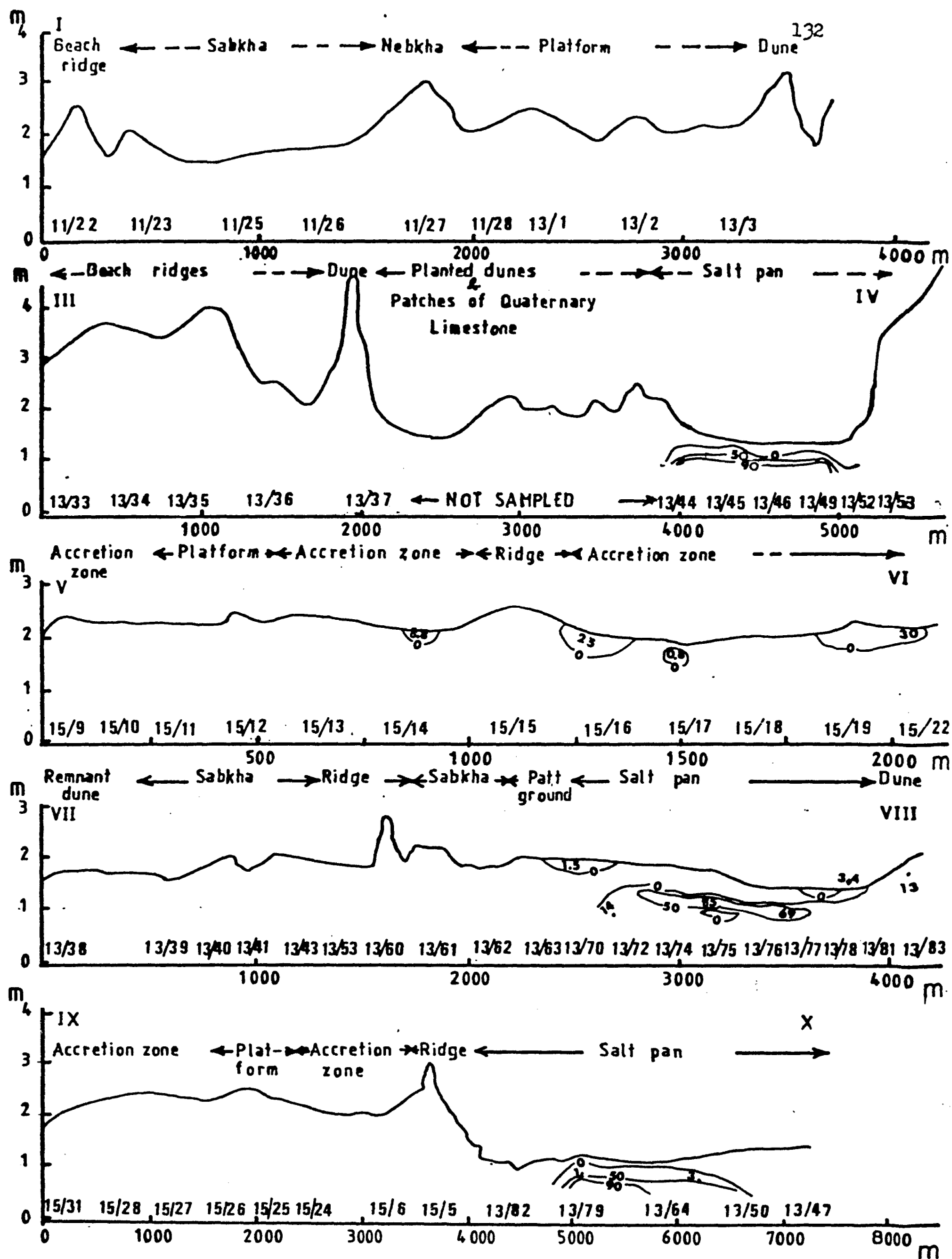


Fig. 3.100 The distribution and percentage of anhydrite in the sediments. Contours at 0.50 and 90%.

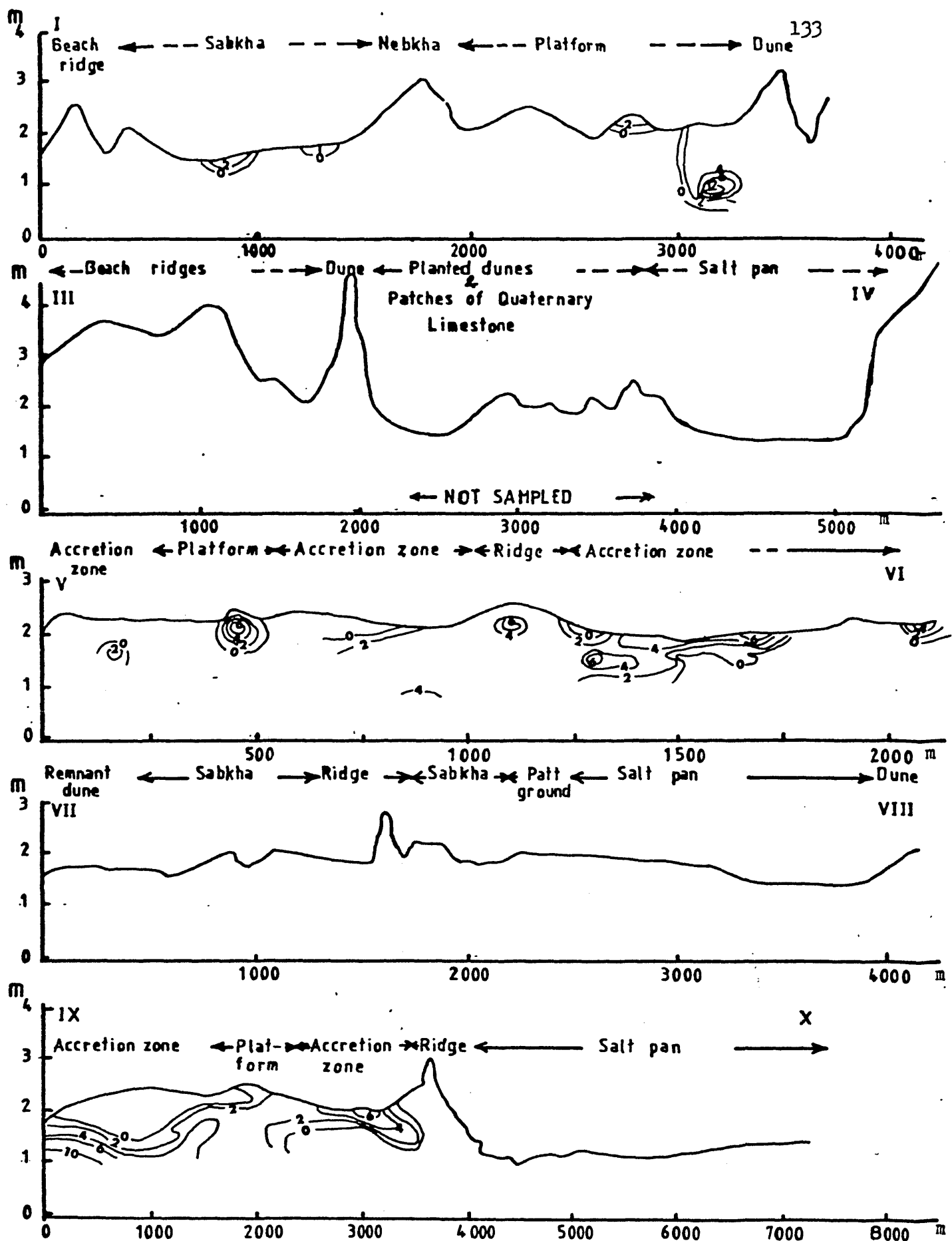


Fig. 3.101 The distribution and percentage of celestite in the sediments.  
C.I. = 2 up to 6% and then values of contours.

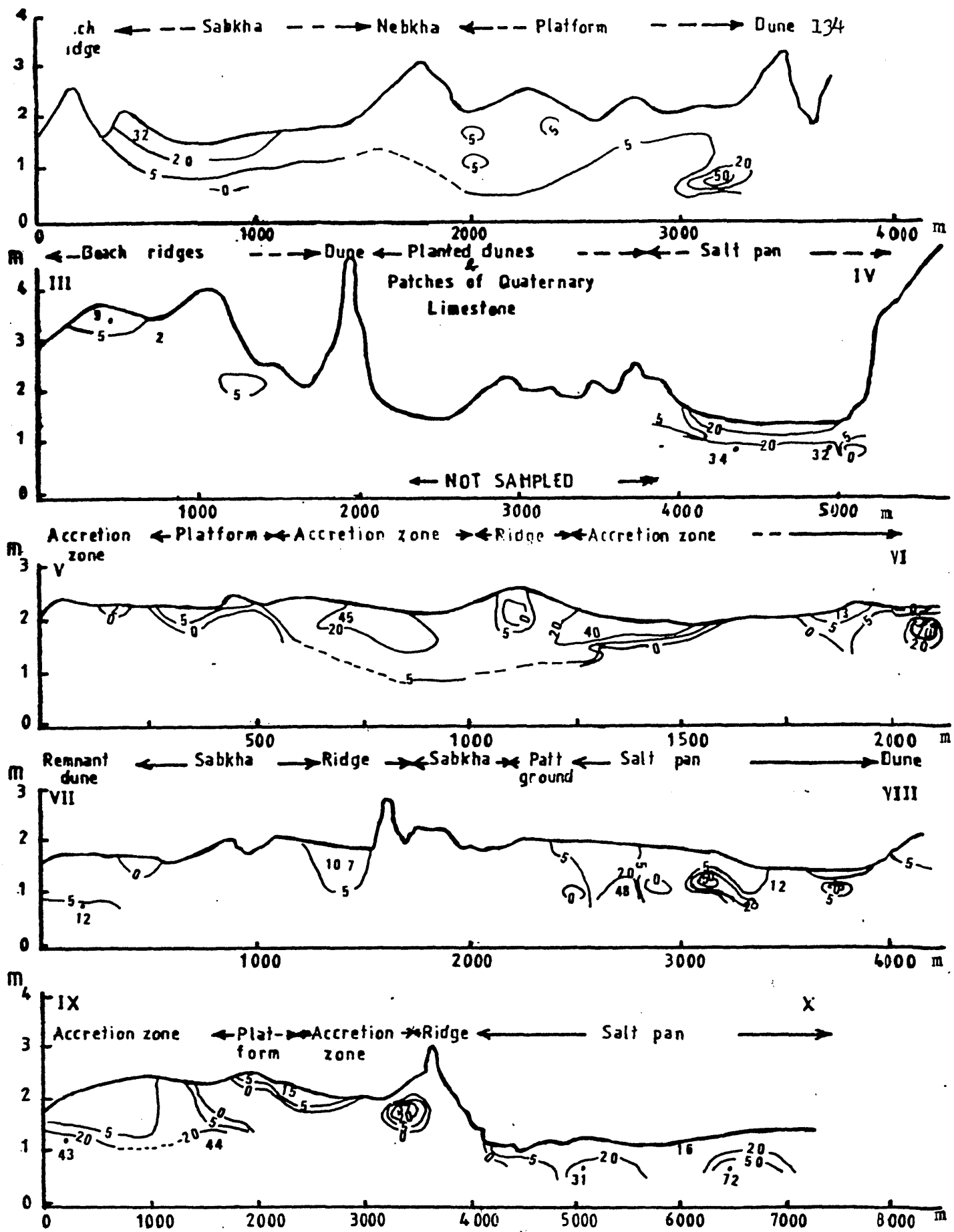


Fig. 3.102 The distribution and percentage of silt plus clay grade material in the sediments. Contours at 0,5,20 and 50%.

#### CHAPTER FOUR

The chemistry of the sediments and of the  
groundwaters, and the diagenesis of the  
sediments

#### 4. Introduction:

The physical and mineralogical properties of the sediments have been discussed in Chapter Three. In this chapter, the chemistry of the sediments and of the groundwaters, and the diagenesis of the sediments will be discussed.

#### 4.1 The Chemistry of the Sediments:

In this section the chemical composition of the sediments with respect to the distribution of some major elements within the sedimentary units is discussed. The trace elements are generally very low and will not be further discussed unless they are of particular significance. The distribution of the units is shown in Figure 3.91.

The chemical compositions are expressed as the percentage of the oxides for the major elements, and as parts per million (p.p.m.) of the trace elements for the whole of the sample (both the sand and silt plus clay grades). The chemical compositions are plotted and contoured (see Figs. 4.1 to 4.8 and Appendix 3).

##### 4.1.1 The Chemical Composition of the Sediments of Unit 1:

##### 4.1.1.a Carbon Dioxide ( $\text{CO}_2\%$ , Fig. 4.1):

The concentration of carbon dioxide in the sediments of Unit 1 varies from 3 to 15.5%; the sediments of Unit 1 occurring in pits at profile I - II have the higher concentration of carbon dioxide ranging from 8 - 15.5%, while those occurring in profile VII - VIII have the lower concentration values of carbon dioxide ranging from 3 to 6.5% (Fig. 4.1). This corresponds to the mineralogy; where the higher percentage of the carbon^{ate} minerals occurs in the sediments of Unit 1 at profile I - II and the lower percentage of carbonate minerals occurs in the sediments of Unit 1 at profile VII - VIII (see Section 3.1).

##### 4.1.1.b Calcium Oxide ( $\text{CaO}\%$ , Fig. 4.2):

The concentration of calcium oxide in the sediments of Unit 1 follows a similar trend to both the percentage of carbonate minerals and the concentration of carbon dioxide (compare Figs. 4.1, 4.2 and 3.94); whereby at profile I - II the concentration of calcium oxide in the sediments ranges from 9 to 18%, while at profile VII - VIII it ranges from 5 to 8.3%.

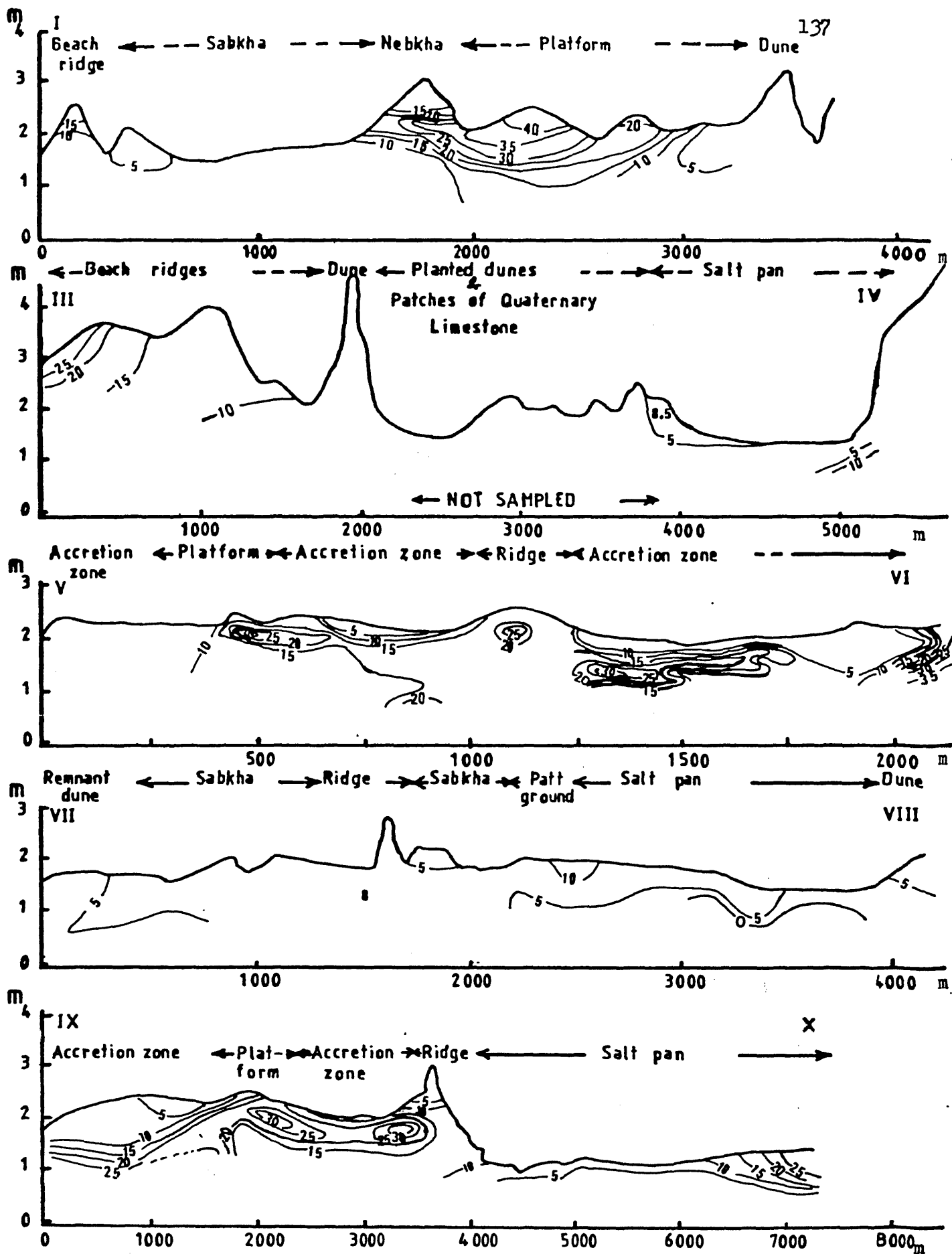


Fig. 4.1 The distribution and percentage of carbon dioxide in the sediments. Contour interval (C.I.) = 5.

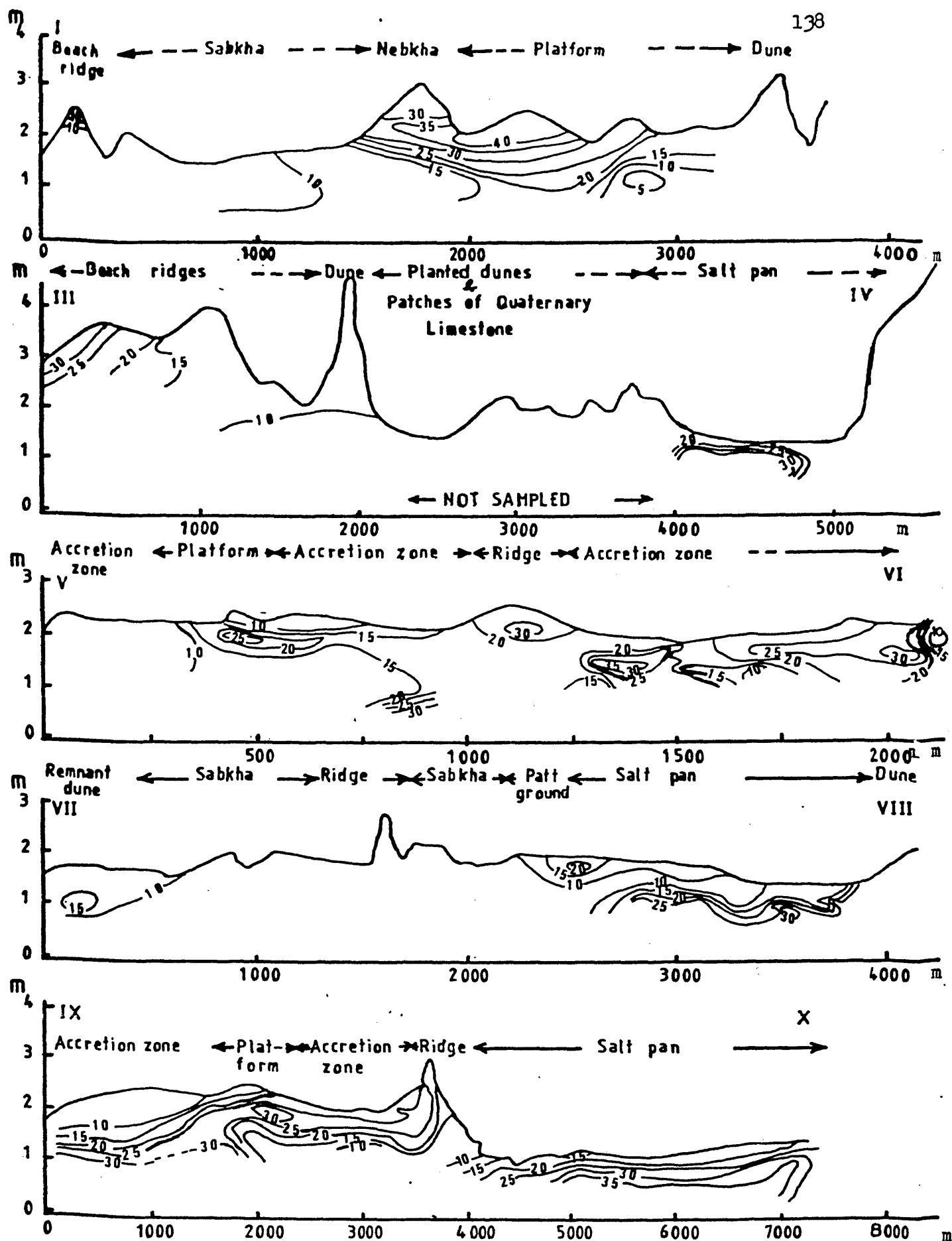


Fig. 4.2 The distribution and percentage of calcium oxide in the sediments, G.I. = 5.

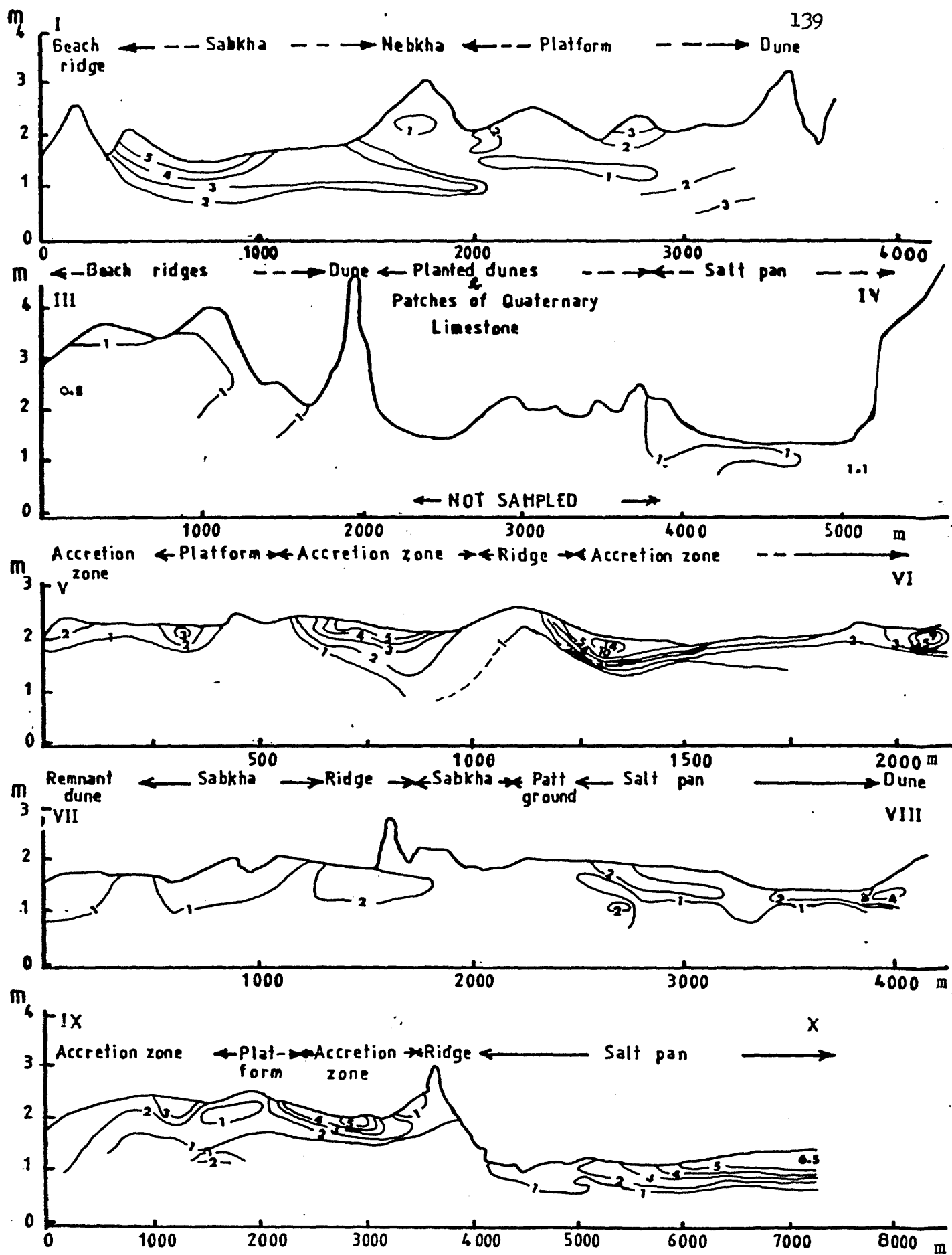


Fig. 4.3 The distribution and percentage of magnesium oxide in the sediments. C.I. = 1 until 5, then C.I. = 5.

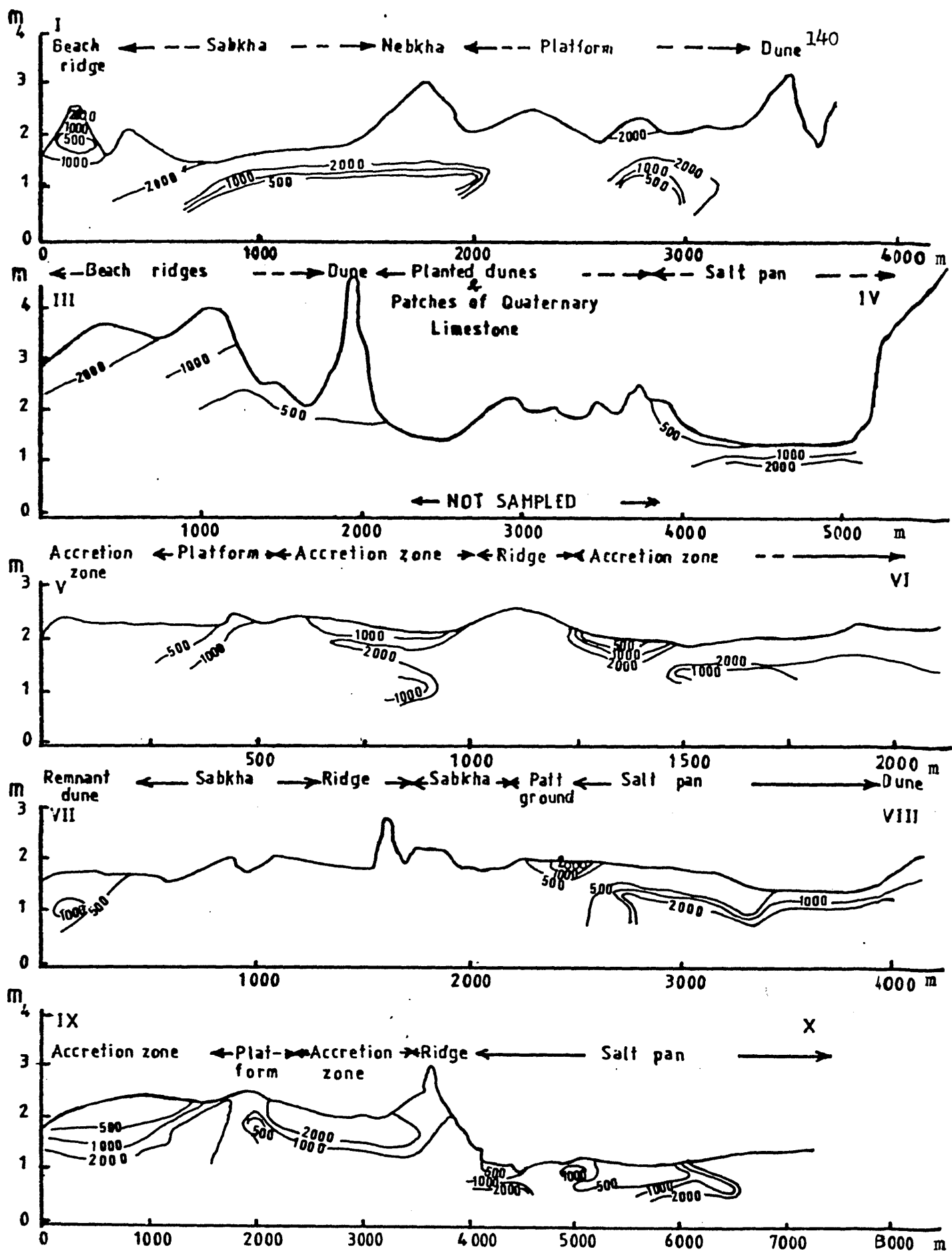


Fig. 4.4 The distribution of strontium (in p.p.m.) in the sediments.  
C.I. = 500, 1,000 and 2,000.

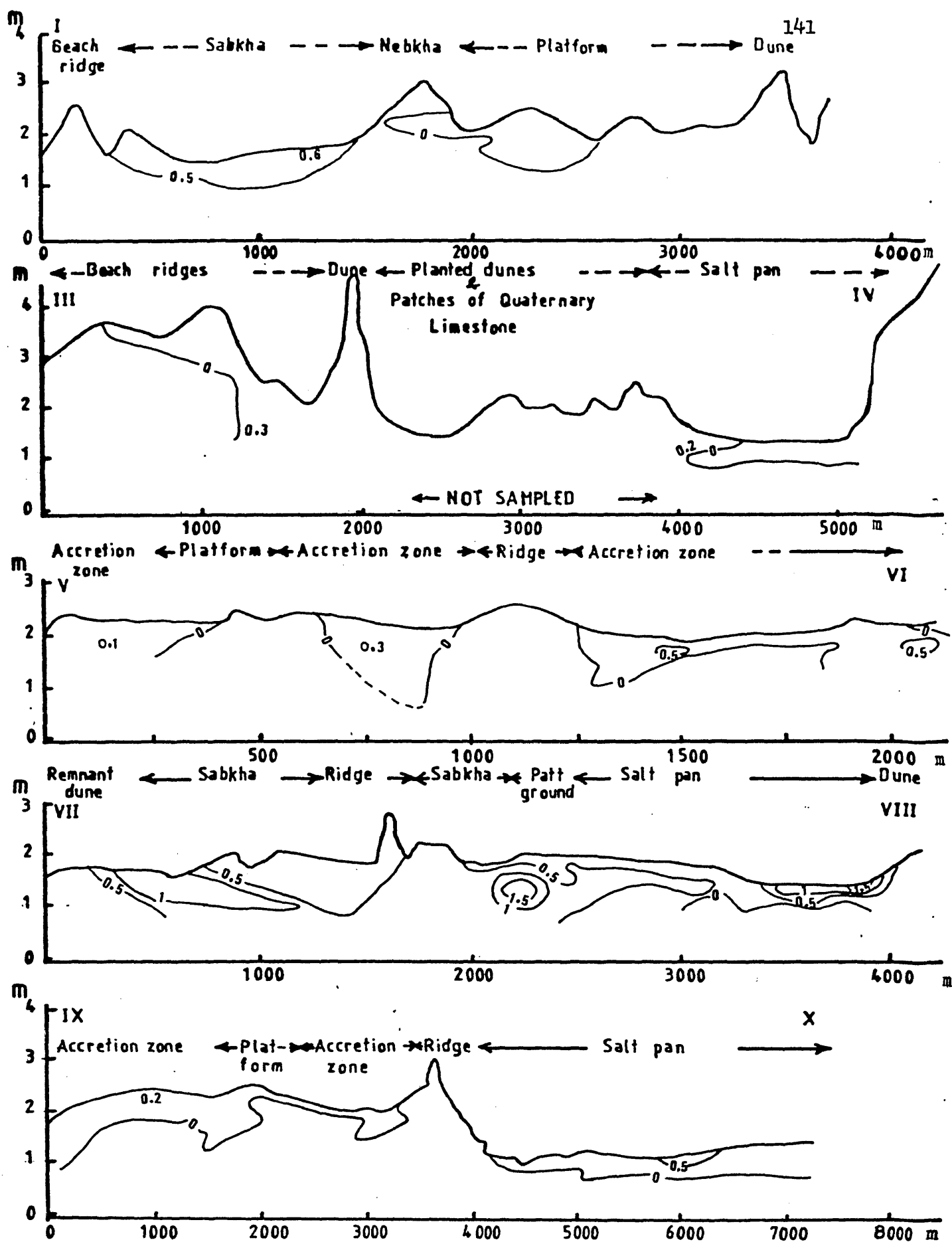


Fig. 4.5 The distribution and percentage of iron oxide in the sediments.  
C.I. = 0.5.

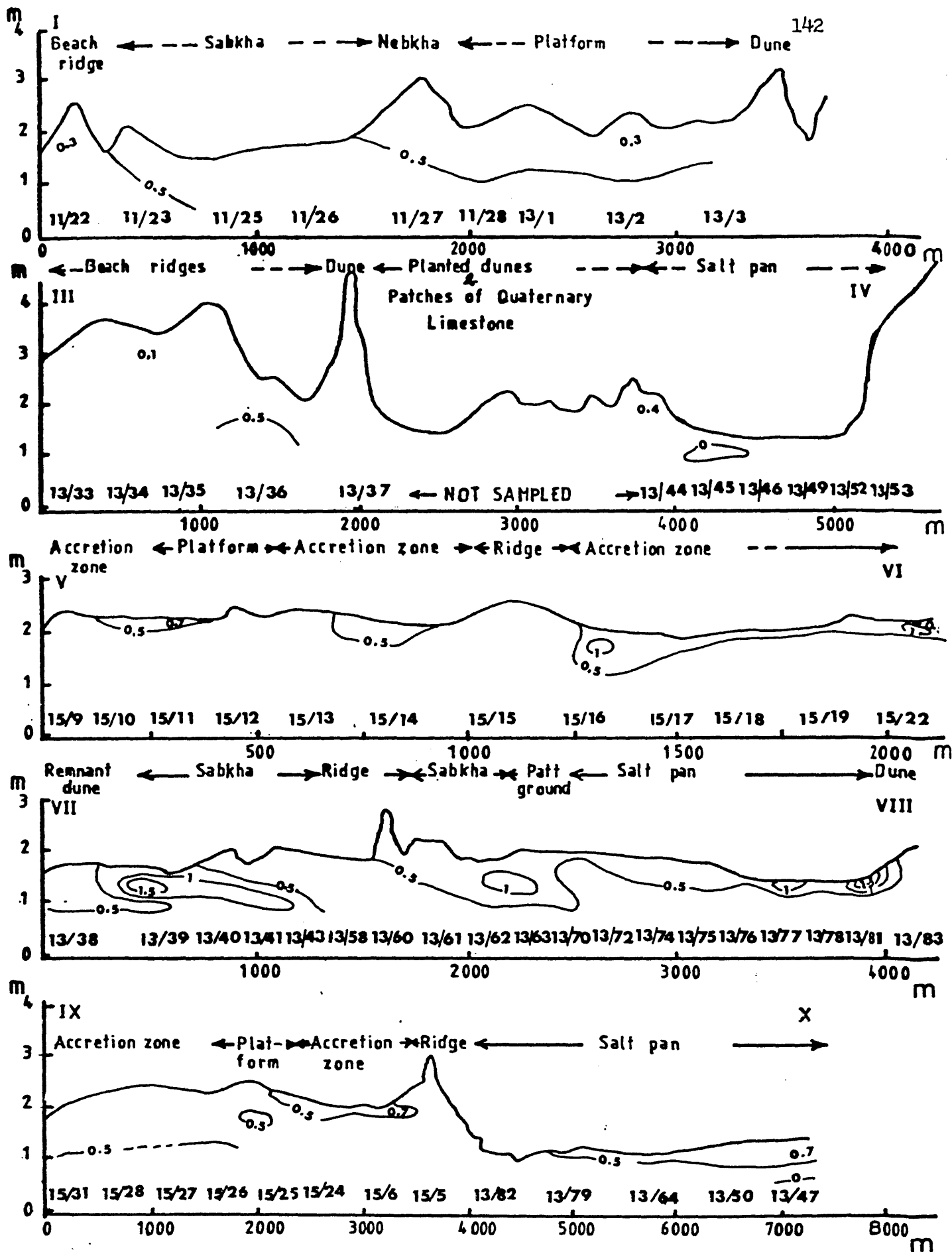


Fig. 4.6 The distribution and percentage of aluminium oxide in the sediments. C.I., = 0.5.

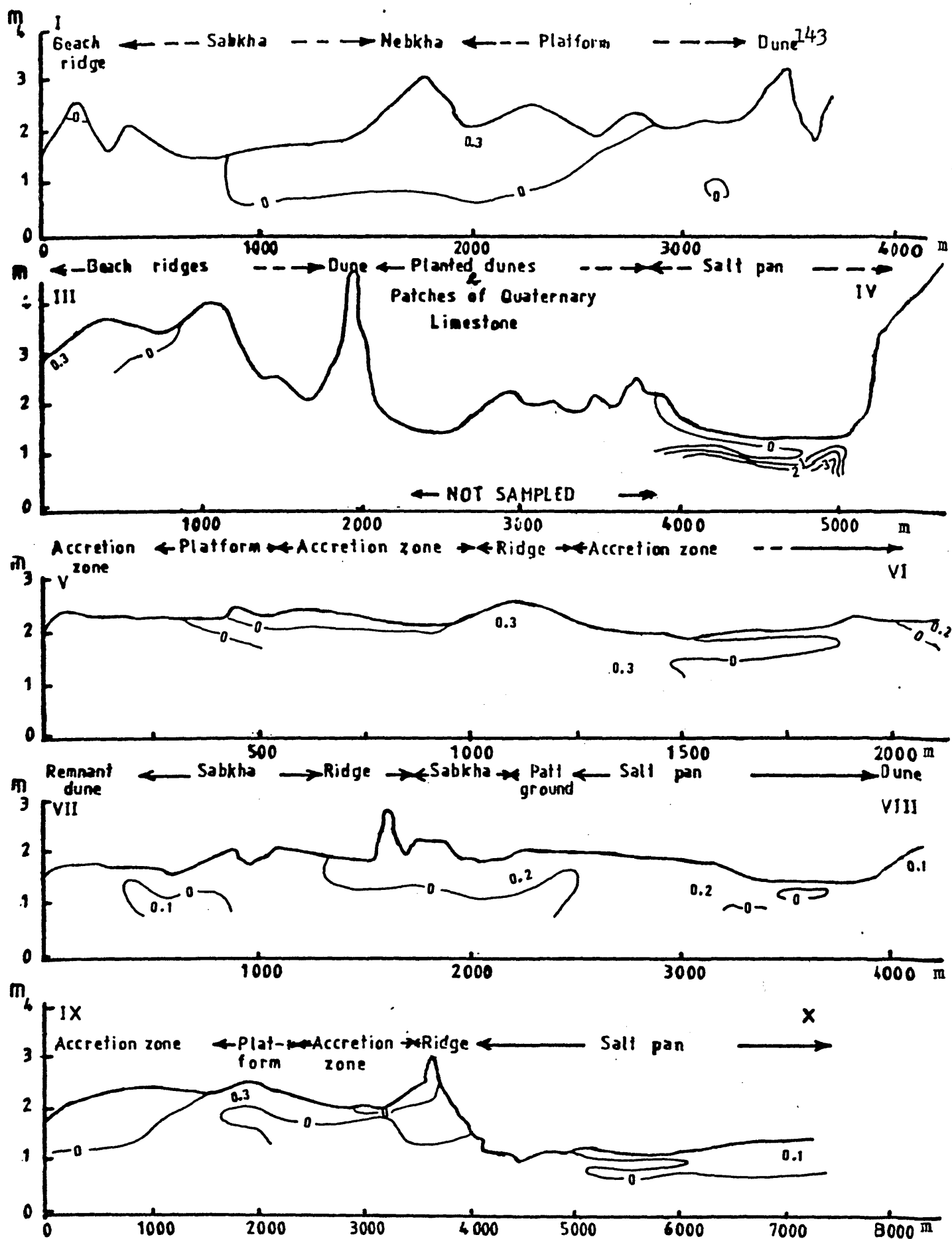


Fig. 4.7 The distribution and percentage of sodium oxide in the sediments. C.I. = 1.

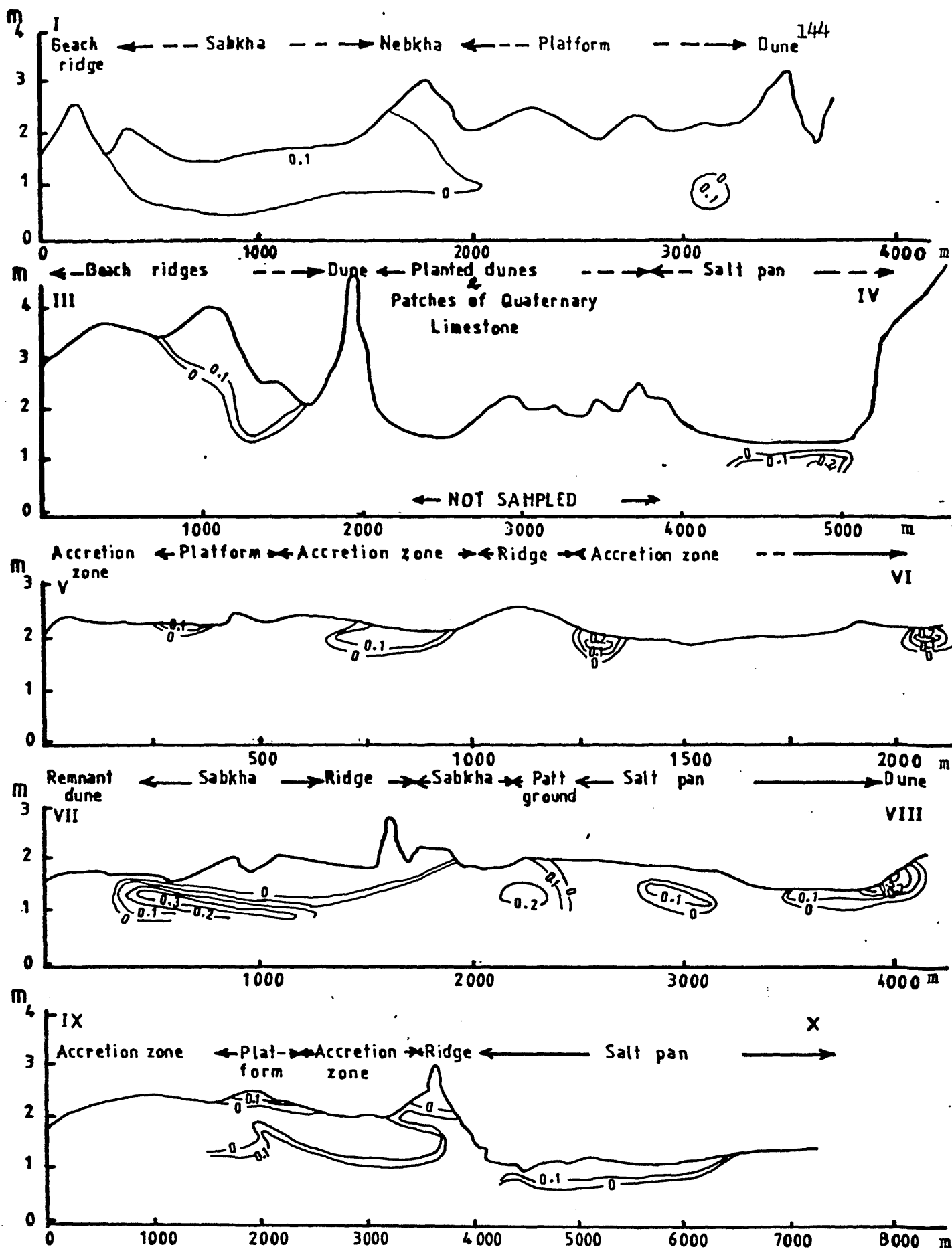


Fig. 4.8 The distribution and percentage of potassium oxide in the sediments, C.I. = 0.1.

#### 4.1.1.c Magnesium Oxide ( $\text{MgO}\%$ , Fig. 4.3):

The concentration of magnesium oxide in the sediments of Unit 1 generally ranges from 1.5 to 2% apart from at pit 13/3 (Fig. 4.3) where it is 3.4%. Some of the magnesium oxide present in the sediments is found in both dolomite and high magnesium calcite, but the amount of dolomite (1.5 - 2.5%) and high magnesium calcite (0 - 2%) (see Section 3.1) does not suffice to account for the amount of magnesium oxide present. Magnesium oxide is also present in some of the heavy minerals (see Section 3.1).

#### 4.1.1.d Strontium (Sr in p.p.m., Fig. 4.4):

Strontium is closely linked with the mineralogy, and its presence depends on the presence of aragonite and celestite, and to a less extent on the presence of gypsum and anhydrite (Kinsman, 1964; Butler, 1973).

In the sediments of Unit 1, the concentrations of strontium are generally less than 500 p.p.m. in profile VII - VIII, while in profile I - II they are generally more than 2,000 p.p.m. (Fig. 4.4). This data agrees well with the higher percentage of aragonite in the sediments of profile I - II, and the lower values of aragonite in the sediments of profile VII - VIII (see Section 3.1).

#### 4.1.1.e Iron Oxide ( $\text{Fe}_2\text{O}_3\%$ , Fig. 4.5):

The concentration of iron oxide in the sediments of Unit 1 is generally low; the sediments contain between 0.3 - 0.6% iron oxide, the lower values (0.3%) are those in profile I - II, while the higher values (0.6%) are those in profile VII - VIII (Fig. 4.5). Iron oxide is present in heavy minerals and in the sediments of Unit 1 blue and green amphiboles and magnetite are present (see Section 3.1).

#### 4.1.1.f Aluminium Oxide ( $\text{Al}_2\text{O}_3\%$ , Fig. 4.6), Sodium Oxide ( $\text{Na}_2\text{O}\%$ , Fig. 4.7) and Potassium Oxide ( $\text{K}_2\text{O}\%$ , Fig. 4.8):

The concentration of aluminium oxide in the sediments of Unit 1 has a similar trend to the concentration of iron oxide, and has concentrations ranging from 0.5 to 0.7% (Fig. 4.6). The concentrations of sodium oxide and potassium oxide are generally low; those for sodium oxide range from 0.05 to 0.1% (Fig. 4.7), while those for potassium oxide range from 0.05 to 0.08%.

Aluminium oxide, sodium oxide and potassium oxide are present in the feldspars and heavy minerals (see Section 3.1).

#### 4.1.2 The Chemical Composition of the Sediments of Unit 2:

##### 4.1.2.a Carbon Dioxide ( $\text{CO}_2\%$ , Fig. 4.1):

The concentration of carbon dioxide in the sediments of Unit 2 varies from 4 to 8% (Fig. 4.1). The higher concentration values are in the sediments in profile I - II and corresponds to the higher percentage of carbonate minerals (see Section 3.2).

##### 4.1.2.b Calcium Oxide ( $\text{CaO}\%$ , Fig. 4.2):

The concentration of calcium oxide in the sediments of Unit 2 follows a similar trend to the concentration of carbon dioxide, and range from 4.5 to 12.9%. The higher concentrations are in the sediments of profile I - II. Calcium oxide is mainly present in the carbonate minerals (see Section 3.2).

##### 4.1.2.c Magnesium Oxide ( $\text{MgO}\%$ , Fig. 4.3):

The concentrations of magnesium oxide in the sediments of Unit 2 range from 0.4 to 2%, but the majority of the samples have a concentration of magnesium oxide ranging from 0.7 to 1% (Fig. 4.3). This data agrees with the mineralogy, where dolomite ranges from 1.8 to 5% and high-magnesium calcite ranges from 0.0 to 2.5% (see Section 3.2). The higher concentration of magnesium oxide lie where there is an increase in dolomite and high-magnesium calcite.

##### 4.1.2.d Strontium (Sr in p.p.m., Fig. 4.4):

The concentrations of strontium in the sediments of Unit 2 are generally low, ranging from 100 to 600 p.p.m., but generally having a value of 300 p.p.m. At pit 13/3 (Fig. 4.4) the sediments of Unit 2 have a concentration of strontium of 12,300 p.p.m., and this corresponds with the presence of celestite (Section 3.2).

##### 4.1.2.e Iron Oxide ( $\text{Fe}_2\text{O}_3\%$ , Fig. 4.5):

The concentration of iron oxide in the sediments of Unit 2 ranges from 0 to 1.73%. The low concentrations of iron oxide in the sediments of Unit 2 are generally present in profile I - II, while the high concentrations are towards profile VII - VIII. Iron oxide is present in magnetite and other heavy minerals (see Section 3.2).

4.1.2.f Aluminium Oxide ( $\text{Al}_2\text{O}_3\%$ , Fig. 4.6), Sodium Oxide ( $\text{Na}_2\text{O}\%$ , Fig. 4.7) and Potassium Oxide ( $\text{K}_2\text{O}\%$ , Fig. 4.8):

The concentration of aluminium oxide in the sediments of Unit 2 ranges from 0.08 to 1.36%. The high concentrations of aluminium oxide are found in the sediments of profile VII - VIII, while the lower values are towards profile I - II (Fig. 4.6).

The concentrations of sodium oxide and potassium oxide in the sediments of Unit 2 follow a similar trend to those of aluminium oxide, and all increase proportionally to each other. The concentrations of sodium oxide range from 0.0 to 0.74% (Fig. 4.7) while those of potassium oxide range from 0.0 to 0.27% (Fig. 4.8). Most of the aluminium oxide, sodium oxide and potassium oxide present in the sediments of Unit 2 are contained in the feldspars and heavy minerals (see Section 3.2).

4.1.3 The Chemical Composition of the Sediments of Unit 3:

4.1.3.A The Chemical Composition of the Sediments of Sub-unit 3a:

4.1.3.A.a Carbon Dioxide ( $\text{CO}_2\%$ , Fig. 4.1):

The concentrations of carbon dioxide in the sediments of Sub-unit 3a have an average of 34% (Fig. 4.1) and this corresponds well with the high percentage of carbonate minerals in the sediments (see Section 3.3.1).

4.1.3.A.b Calcium Oxide ( $\text{CaO}\%$ , Fig. 4.2):

The concentrations of calcium oxide in the sediments of Sub-unit 3a follow a similar trend to those of carbon dioxide (compare Figs. 4.1 and 4.2), and have an average of 37% (Fig. 4.2). Calcium oxide in this sub-unit is present in the carbonate minerals (see Section 3.3.1).

4.1.3.A.c Magnesium Oxide ( $\text{MgO}\%$ , Fig. 4.3):

The concentrations of magnesium oxide in the sediments of Sub-unit 3a have an average value of 1.8% and can be accounted for by the high-magnesium calcite and dolomite present in the sediments (see Section 3.3.1).

#### 4.1.3.A.d Strontium Oxide (Sr in p.p.m., Fig. 4.4):

The concentrations of strontium in the sediments of Sub-unit 3a are generally higher than 2,000 p.p.m. These high values agree well with the high concentration of aragonite in the sediments (aragonite ranges from 48 - 65%, see Section 3.3.1).

#### 4.1.3.A.e Iron Oxide ( $\text{Fe}_2\text{O}_3\%$ , Fig. 4.5):

The concentrations of iron oxide in the sediments of Sub-unit 3a are generally low, ranging from 0.01 to 0.09%, and are due to the small amount of magnetite and other heavy minerals present (see Section 3.3.1).

#### 4.1.3.A.f Aluminium Oxide ( $\text{Al}_2\text{O}_3\%$ , Fig. 4.6), Sodium Oxide ( $\text{Na}_2\text{O}\%$ , Fig. 4.7) and Potassium Oxide ( $\text{K}_2\text{O}$ , Fig. 4.8):

The concentrations of aluminium oxide, sodium oxide and potassium oxide in the sediments of Sub-unit 3a are generally low. The aluminium oxide values have an average of 0.2%, while those for sodium oxide average 0.26%, and those for potassium oxide are very low.

#### 4.1.3.B The Chemical Composition of the Sediments of Sub-unit 3b:

##### 4.1.3.B.a Carbon Dioxide ( $\text{CO}_2\%$ , Fig. 4.1):

The concentrations of carbon dioxide in the sediments of Sub-unit 3b range from 7 to 21% (Fig. 4.1). In profile III - IV the higher carbon dioxide values are those towards the sea, and these gradually decrease in an inland direction, while in profile IX - X the concentration of carbon dioxide increases gradually until pit 15/27 (Fig. 4.1) and then gradually decreases in an inland direction.

##### 4.1.3.B.b Calcium Oxide ( $\text{CaO}\%$ , Fig. 4.2):

The concentrations of calcium oxide in the sediments of Sub-unit 3b follow a similar trend to the concentrations of carbon dioxide and to the percentage of carbonate minerals (compare Figs. 3.94, 4.1 and 4.2; also see Section 3.3.2). Calcium oxide concentrations range from 10 to 24.5% (Fig. 4.2).

##### 4.1.3.B.c Magnesium Oxide ( $\text{MgO}\%$ , Fig. 4.3):

The concentration of magnesium oxide in the sediments of Sub-unit 3b range from 0.5 to 1% (Fig. 4.3). The higher concentrations correspond with an increase in dolomite and high-magnesium calcite

(compare Figs. 4.3 with 3.97 and 3.98). In profile III - IV, the concentration of magnesium oxide gradually decreases from 0.8%, towards the sea, to 0.6%, and then at pit 13/36 there is an increase to 1% (Fig. 4.3), which is matched with an increase in dolomite (see Fig. 3.98, and Section 3.3.2).

#### 4.1.3.B.d Strontium (Sr in p.p.m., Fig. 4.4):

The concentration of strontium in the sediments of Sub-unit 3b is closely related to the amount of aragonite present; as aragonite decreases inland so does the concentration of strontium (compare Fig. 4.4 with Fig. 3.96). The concentrations of strontium range from 600 to more than 2,000 p.p.m. (Fig. 4.4).

#### 4.1.3.B.e Iron Oxide ( $\text{Fe}_2\text{O}_3\%$ , Fig. 4.5):

The concentrations of iron oxide in the sediments of Sub-unit 3b are generally low, ranging from 0.0 to 0.3%, due to the small number of magnetite and other heavy minerals present in the sediments (see Section 3.3.2).

#### 4.1.3.B.f Aluminium Oxide ( $\text{Al}_2\text{O}_3\%$ , Fig. 4.6), Sodium Oxide ( $\text{Na}_2\text{O}\%$ , Fig. 4.7) and Potassium Oxide ( $\text{K}_2\text{O}\%$ , Fig. 4.8):

The concentrations of aluminium oxide, sodium oxide and potassium oxide in the sediments of Sub-unit 3b are generally low; the aluminium oxide values range from 0.1 to 0.44% (Fig. 4.6), those for sodium oxide range from 0.04 to 0.1% (Fig. 4.7), and those for potassium oxide are generally lower than 0.08% having an average of 0.01%. These low values are due to the low feldspar content in the sediments (see Section 3.3.2).

### 4.1.4 The Chemical Composition of the Sediments of Unit 4:

#### 4.1.4.A The Chemical Composition of the Sediments of Sub-unit 4a:

##### 4.1.4.A.a Carbon Dioxide ( $\text{CO}_2\%$ , Fig. 4.1):

The concentrations of carbon dioxide in the sediments of Sub-unit 4a are high, ranging from 21 to 40% (Fig. 4.1), and correspond with the high values of carbonate minerals present in the sediments (compare Figs. 4.1 and 3.94, and see Section 3.4.1).

##### 4.1.4.A.b Calcium Oxide ( $\text{CaO}\%$ , Fig. 4.2):

The concentrations of calcium oxide in the sediments of Sub-unit

4a are also high and follow a similar trend to both the concentration of carbon dioxide and the percentage of carbonate minerals (compare Figs. 4.1, 4.2 and 3.94). The concentrations range from 25 to 40% (Fig. 4.2).

#### 4.1.4.A.c Magnesium Oxide ( $\text{MgO}\%$ , Fig. 4.3):

The concentration of magnesium oxide in the sediments of Sub-unit 4a is 1% (Fig. 4.3), and corresponds with the dolomite and high-magnesium calcite present (see Section 3.4.1).

#### 4.1.4.A.d Strontium (Sr in p.p.m., Fig. 4.4):

The concentrations of strontium in the sediments of Sub-unit 4a are generally higher than 2,000 p.p.m. (Fig. 4.4) and this agrees well with the high percentage of aragonite (65 - 86%) present in the sediments (see Section 3.4.1).

#### 4.1.4.A.e Iron Oxide ( $\text{Fe}_2\text{O}_3\%$ , Fig. 4.5):

The concentrations of iron oxide in the sediments of Sub-unit 4a are generally low; less than 0.04%, and this is due to the small amounts of heavy minerals present (see Section 3.4.1).

#### 4.1.4.A.f Aluminium Oxide ( $\text{Al}_2\text{O}_3\%$ , Fig. 4.6), Sodium Oxide ( $\text{Na}_2\text{O}\%$ , Fig. 4.7) and Potassium Oxide ( $\text{K}_2\text{O}\%$ , Fig. 4.8):

The concentrations of aluminium oxide, sodium oxide and potassium oxide are generally low; the concentrations of aluminium oxide are generally less than 0.2% (Fig. 4.6), those for sodium oxide are less than 0.3% (Fig. 4.7) and those for potassium oxide are less than 0.05% (Fig. 4.8). These low values are mainly due to the small amount of feldspars present (see Section 3.4.1).

#### 4.1.4.B The Chemical Composition of the Sediments of Sub-unit 4b:

##### 4.1.4.B.a Carbon Dioxide ( $\text{CO}_2\%$ , Fig. 4.1):

The concentrations of carbon dioxide in the sediments of Sub-unit 4b range from 9 to 30.5% (Fig. 4.1). In profile I - II, the concentration of carbon dioxide is 15.4%. In profile III - IV, the concentration decreases in an inland direction; from 26% seawards to 9% landwards (Fig. 4.1). In profile V - VI, there is an increase in the concentrations in an inland direction from 9% seawards to 29% landwards. In profile IX - X, there is also an increase in the

concentrations in an inland direction from 20% to 30% and in pit 15/5 further inland it drops to 1%. All these various ranges correspond to the carbonate minerals present (see Section 3.4.2).

#### 4.1.4.B.b Calcium Oxide ( $\text{CaO}\%$ , Fig. 4.2):

The concentrations of calcium oxide in the sediments of Sub-unit 4b follow a similar trend to both the concentrations of carbon dioxide and the percentage of carbonate minerals present (compare Fig. 4.1, 4.2 and 3.94 and see Section 3.4.2). The concentrations range from 10 to 34% (Fig. 4.2).

#### 4.1.4.B.c Magnesium Oxide ( $\text{MgO}\%$ , Fig. 4.3):

The concentrations of magnesium oxide in the sediments of Sub-unit 4b are closely related to the dolomite and high-magnesium calcite present (compare Fig. 4.3, 3.97 and 3.98, and see Section 3.4.2). The concentrations of magnesium oxide range from 0.3 to 1.7%.

#### 4.1.4.B.d Strontium (Sr in p.p.m., Fig. 4.4):

The concentrations of strontium in the sediments of Sub-unit 4b range from 600 to more than 2,000 p.p.m. (Fig. 4.4). The lower concentrations are present where there is a decrease in aragonite, while the higher values are where there is abundant aragonite (compare Figs. 4.4 and 3.96, and see Section 3.4.2).

#### 4.1.4.B.e Iron Oxide ( $\text{Fe}_2\text{O}_3\%$ , Fig. 4.5):

The concentrations of iron oxide in the sediments of Sub-unit 4b are generally low, ranging from 0.0 to 0.3%, (Fig. 4.5), and the majority of samples have less than 0.1% concentrations of iron oxide. These low concentrations are due to the very small amount of heavy minerals present (see Section 3.4.2).

#### 4.1.4.B.f Aluminium Oxide ( $\text{Al}_2\text{O}_3\%$ , Fig. 4.6), Sodium Oxide ( $\text{Na}_2\text{O}\%$ , Fig. 4.7) and Potassium Oxide ( $\text{K}_2\text{O}\%$ , Fig. 4.8):

The concentrations of aluminium oxide, sodium oxide and potassium oxide in the sediments of Sub-unit 4b are generally low; those of aluminium oxide have an average of 0.1% (Fig. 4.6), those of sodium oxide range from 0.04 to 0.31% (Fig. 4.7), and those of potassium oxide have an average of 0.04% (Fig. 4.8). Aluminium oxide, sodium oxide and potassium oxide are present in feldspars and heavy minerals (see Section 3.4.2).

#### 4.1.4.C The Chemical Composition of the Sediments of Sub-unit 4c.

##### 4.1.4.C.a Carbon Dioxide ( $\text{CO}_2\%$ , Fig. 4.1):

The concentrations of carbon dioxide in the sediments of Sub-unit 4c range from 6 to 14% (Fig. 4.1) and corresponds with the percentage of carbonate minerals present (see Section 3.4.3).

##### 4.1.4.C.b Calcium Oxide ( $\text{CaO}\%$ , Fig. 4.2):

The concentrations of calcium oxide in the sediments of Sub-unit 4c follow a similar trend to both the concentrations of carbon dioxide and the percentage of carbonate minerals (see Figs. 4.1, 4.2 and 3.94 and Section 3.4.3).

##### 4.1.4.C.c Magnesium Oxide ( $\text{MgO}\%$ , Fig. 4.3):

The concentrations of magnesium oxide in the sediments of Sub-unit 4c range from 0.6 to 2.3% (Fig. 4.3). The amount of high-magnesium calcite plus dolomite does not suffice the amount of magnesium oxide present. Magnesium oxide may also be present in the heavy minerals.

##### 4.1.4.C.d Strontium (Sr in p.p.m., Fig. 4.4):

The concentrations of strontium in the sediments of Sub-unit 4c range from 400 to more than 2,000 p.p.m., and the high values of strontium correspond to the presence of aragonite and celestite (see Section 3.4.3).

##### 4.1.4.C.e Iron Oxide ( $\text{Fe}_2\text{O}_3\%$ , Fig. 4.5):

The concentration of iron oxide in the sediments of Sub-unit 4c are generally low and have an average of 0.1% (Fig. 4.5) and this corresponds with the small amount of heavy minerals present.

##### 4.1.4.C.f Aluminium Oxide ( $\text{Al}_2\text{O}_3\%$ , Fig. 4.6) Sodium Oxide ( $\text{Na}_2\text{O}\%$ , Fig. 4.7) and Potassium Oxide ( $\text{K}_2\text{O}\%$ , Fig. 4.8):

The concentrations of aluminium oxide, sodium oxide and potassium oxide in the sediments of Sub-unit 4c are generally low; the concentrations of aluminium oxide average 0.3% (Fig. 4.6). Those of sodium oxide average 0.04%, and those of potassium oxide have an average of 0.01%.

#### 4.1.4.D The Chemical Composition of the Sediments of Sub-unit 4d:

##### 4.1.4.D.a Carbon Dioxide ( $\text{CO}_2\%$ , Fig. 4.1):

The concentration of carbon dioxide in the sediments of Sub-unit 4d ranges from 16 to 31% (Fig. 4.1). Seawards the concentrations are 30%, and gradually decrease to 16% in pit 15/14 and then increase in a landward direction to 31% (Fig. 4.1). These correspond to the percentage of carbonate minerals (see Section 3.4.4).

##### 4.1.4.D.b Calcium Oxide ( $\text{CaO}\%$ , Fig. 4.2):

The concentrations of calcium oxide in the sediments of Sub-unit 4d range from 18 to 35% (Fig. 4.2) and follow a similar trend to both the percentage of carbonate minerals and the concentrations of carbon dioxide (see Section 3.4.4).

##### 4.1.4.D.c Magnesium Oxide ( $\text{MgO}\%$ , Fig. 4.3):

The concentrations of magnesium oxide in the sediments of Sub-unit 4d gradually increase from 0.4% (pit 15/12) to 8.5% (pit 15/17) and decreases again to 1% (pit 15/18). The percentages of high-magnesium calcite and dolomite (see Section 3.4.4) are not sufficient to produce such high values of magnesium oxide, and the source of this extra magnesium may be from the heavy minerals present and probably the presence of some clay minerals.

##### 4.1.4.D.d Strontium (Sr in p.p.m., Fig. 4.4):

The concentration of strontium in the sediments of Sub-unit 4d are generally high, and have values of more than 2,000 p.p.m. (Fig. 4.4). This corresponds well with the mineralogy, where aragonite (30 - 80%) is abundant, and celestite is present (see Section 3.4.4).

##### 4.1.4.D.e Iron Oxide ( $\text{Fe}_2\text{O}_3\%$ , Fig. 4.5):

The concentrations of iron oxide in the sediments of Sub-unit 4d are low, and have an average of 0.3%, and is due to the small amount of heavy minerals (see Section 3.4.4).

##### 4.1.4.D.f Aluminium Oxide ( $\text{Al}_2\text{O}_3\%$ , Fig. 4.6), Sodium Oxide ( $\text{Na}_2\text{O}\%$ , Fig. 4.7) and Potassium Oxide ( $\text{K}_2\text{O}\%$ , Fig. 4.8):

The concentrations of aluminium oxide, sodium oxide and potassium oxide in the sediments of Sub-unit 4d are generally low; the concentrations

of aluminium oxide range from 0.07 to 0.7% (Fig. 4.6). Those for sodium oxide average 0.2% (Fig. 4.7) and those for potassium oxide range from 0.01 to 0.1% (Fig. 4.8).

#### 4.1.5 The Chemical Composition of the Surface Sediments, the Sediments of the Dunes and the Sediments of the Salt Pan:

##### 4.1.5.A The Chemical Composition of the Surface Sediments of the Ridges (Figs. 4.1 to 4.8):

Sub-unit 4a represents the surface sediments of the ridges, and its chemistry has been discussed previously (see Section 4.1.4.A). The inner ridge, pit 13/62, west of the salt pan has Unit 2 as its surface layer, and its chemistry has also been discussed (Section 4.1.2).

##### 4.1.5.B The Chemical Composition of the Surface Sediments of the Sabkha (Figs. 4.1 to 4.8):

The sediments of Unit 2 represent the surface sediments of the sabkha, and its chemistry has been discussed (Section 4.1.2). Where Unit 2 is overlaid by a gypseous calcareous quartz arenite layer, the chemistry of this upper layer is as follows:

The concentration of carbon dioxide increases in an inland direction from 3.7 to 8% (Fig. 4.1) and corresponds well with the percentage of carbonate minerals. The concentration of calcium oxide in the sediments also increases in the same direction as that of carbon dioxide from 8.3 to 18% (Fig. 4.2). This corresponds to the percentage of carbonate minerals and gypsum. The concentration of magnesium oxide in the sediments is generally high and ranges from 3.5 to 5.5% (Fig. 4.3) and it decreases in an inland direction, the high percentage may be due to the presence of clay minerals. The concentration of strontium increases in an inland direction from 1,500 to more than 2,000 p.p.m. (Fig. 4.4) and this corresponds with an increase in celestite (Section 3.5.2). The concentration of iron oxide is 0.5% and is due to the small amount of heavy minerals present. The concentrations of aluminium oxide, sodium oxide and potassium oxide are generally low; that of aluminium oxide is 0.8%, that of sodium oxide is 0.08%, and that of potassium oxide is 0.06%.

#### 4.1.5.C The Chemical Composition of the Surface Sediments of the Accretion Zone (Figs. 4.1 to 4.8):

The concentrations of aluminium oxide, sodium oxide, potassium oxide and iron oxide are generally low in the surface sediments of the accretion zone and will not be further discussed.

Towards the sea, the surface sediments (pits 15/9, 15/10 and 15/27) have a concentration of carbon dioxide ranging from 2.5 to 8.8% (Fig. 4.1). The higher concentrations are found in the sediments of profile IX - X (Fig. 4.1). The concentration of calcium oxide ranges from 8 to 8.6%, and corresponds to the percentage of carbonate minerals and gypsum (Section 3.5.3). The concentration of magnesium oxide increases in an inland direction from 1.6 to 3.8% (Fig. 4.3) the higher values being in profile IX - X. Magnesium oxide is present in dolomite, high-magnesium calcite and some of the heavy minerals.

The concentration of strontium decreases in an inland direction from more than 2,000 to 300 p.p.m. and follows a similar trend to the carbonate minerals.

Further inland at pits 15/13 and 15/14, the concentrations of carbon dioxide range from 1 to 2.5% (Fig. 4.1) and they decrease in an inland direction. The concentrations of calcium oxide increase in an inland direction from 8 to 11.4% and corresponds well with the presence of gypsum (Section 3.5.3). The concentration of magnesium oxide in the sediments is 5.2%. The concentration of strontium ranges from 400 to 700 p.p.m. and is related to the absence of aragonite and celestite.

Still further inland, pit 15/16, the concentration of carbon dioxide is similar to the seaward sediments, but there is an increase in the concentration of calcium oxide to 19% due to the increase in gypsum and the presence of magnesite increases the concentration of  $MgO$  to 15%. The concentration of strontium increases with depth from 400 to more than 2,000 p.p.m. due to the presence of celestite.

Further inland, pits 15/17, 15/18 and 15/19, the concentration of carbon dioxide increases slightly from the previous pits and ranges from 2.5 - 5%, and corresponds to the percentage of carbonate minerals (Section 3.5.3). The concentrations of calcium oxide increase also

and range from 23 to 27% and correspond to an increase in gypsum (Section 3.5.3). The concentration of magnesium oxide ranges from 1.5 to 5.4% and decreases towards pit 15/19. Magnesium oxide may be present in the dolomite and the heavy minerals. The concentration of strontium is generally more than 2,000 p.p.m. due to the presence of celestite.

#### 4.1.5.D The Chemical Composition of the Surface Sediments of the Platform (Figs. 4.1 to 4.8):

The concentrations of carbon dioxide in the surface sediments of the platform range from 7.5 to 35% (Fig. 4.1). The higher concentrations are found in the sediments of profile I - II, (the quartzose skeletal calcarenites), while the lower concentrations are found in the sediments of profile V - VI (the skeletal calcareous quartz arenites) in the sediments of profile IX - X the concentration is 11%. The concentration of calcium oxide in the sediments ranges from 11% to 41% and follows a similar trend to that of carbon dioxide (compare Figs. 4.1 and 4.2) and corresponds well with the percentages of carbonate minerals and gypsum (Section 3.5.4). The concentration of magnesium oxide in the sediments ranges from 1.5 to 3.5% (Fig. 4.3) and the higher values are also in the sediments of profile I - II, where there is high-magnesium calcite (6.9%) and dolomite (3.1%) and heavy minerals. The concentrations of strontium in the sediments range from 500 to more than 2,000 p.p.m., the higher values are in profile I - II and correspond with the presence of aragonite.

#### 4.1.5.E The Chemical Composition of the Sediments of the Dunes (Appendix 3):

##### 4.1.5.E.a The Chemical Composition of the Aeolian Sands with Dune Forms:

At pits 13/3, 13/83 and 15/6, the concentrations of carbon dioxide range from 1.5 to 5.5% following a similar trend to the carbonate minerals (see Section 3.5.5.a). The concentration of calcium oxide in the sediments ranges from 17.5 to 29% and follows a similar trend to those of carbon dioxide, and corresponds with the percentage of gypsum and carbonate minerals present. The concentration of magnesium oxide ranges from 0.8 to 3.3% and are probably present in high-magnesium calcite and heavy minerals. The concentration of strontium in the sediments ranges from 900 to more than 2,000 p.p.m. The higher values are those in profile I - II, and are due to the presence

of celestite (see Section 3.5.5.A).

#### 4.1.5.E.b The Chemical Composition of the Sediments of the Dunes:

At pit 11/27, the nebkha, the concentration of carbon dioxide in the sediments of the surface layer is 13.8% and corresponds with the percentage of carbonate minerals. The concentration of calcium oxide is 29.7% and corresponds with the percentage of carbonate minerals and gypsum. The concentration of magnesium oxide is 1.6%, and is present in dolomite and heavy minerals (see Section 3.5.5.b). The concentration of strontium in the sediments is more than 2,000 p.p.m. and corresponds with the aragonite present in the sediments (Section 3.5.5.b).

The chemistry of the other dunes present in the area of study is:

The concentration of carbon dioxide in the sediments ranges from 4.3 to 11.4% and corresponds to the percentage of carbonate minerals present, the higher values are found towards profile I - II, while the lower values are found towards profile III - IV. The concentration of calcium oxide in the sediments ranges from 8 to 14% and follows a similar trend to that of carbon dioxide and corresponds to the percentage of carbonate minerals and gypsum present. The concentration of magnesium oxide ranges from 0.75 to 1%, the lower values are found towards profile I - II, this agrees well with the presence of dolomite. The concentration of strontium in the sediments is only 600 p.p.m., and is due to the low percentage of aragonite present (see Section 3.5.5.b).

#### 4.1.5.F The Chemical Composition of the Sediments of the Salt Pan (Figs. 4.1 to 4.8):

##### 4.1.5.F.a The Chemical Composition of the Sediments of Sub-unit a:

The concentration of carbon dioxide in the sediments ranges from 0.4 to 1.2% and corresponds with the mineralogy which shows that there is a small amount of carbonate present. (Section 3.5.6.a.1). The concentrations of calcium oxide range from 13 to 34.5% which correspond to the amount of anhydrite and gypsum present. The concentrations of magnesium oxide range from 1 to 1.8%, since the amount of carbonate minerals is too low to explain the magnesium oxide, then magnesite is probably present in a small amount which was not detected by the XRD

technique. The concentration of strontium ranges from 600 to 6,000 p.p.m. Part of this strontium may be incorporated within the anhydrite and gypsum crystal lattices (this has been shown by Kinsman, 1964, and Butler, 1973).

#### 4.1.5.F.b The Chemical Composition of the Sediments of Sub-unit b:

The concentration of carbon dioxide in the sediments ranges from 0.6 to 1.5%, indicating a low concentration of carbonates present. The concentration of calcium oxide ranges from 30 to 32.8% and corresponds with the amount of gypsum present. The concentrations of magnesium oxide range from 0.15 to 0.63%, and magnesite is probably present in a small amount. The concentrations of strontium range from 900 to more than 2,000 p.p.m. Celestite is probably present in small amounts since the amount of carbonate minerals present is too low to explain the presence of strontium. Part of this strontium is incorporated in the crystal lattices of gypsum.

#### 4.1.5.F.c The Chemical Composition of the Sediments of Sub-unit c:

The concentrations of carbon dioxide in the sediments have an average of 1.9% and corresponds with the carbonate minerals. The concentrations of calcium oxide have an average of 25.1% and correspond to the gypsum. The concentrations of magnesium oxide average 0.7%, and may be due to the heavy minerals present. That of strontium is 700 p.p.m. This small amount of strontium may be incorporated in the gypsum crystal lattice.

#### 4.1.5.F.d The Chemical Composition of the Sediments of Sub-unit d:

The concentrations of carbon dioxide in the sediments range from 5 to 9%, and the concentrations of calcium oxide ranges from 12 - 19% and corresponds to the carbonate minerals and gypsum present. The concentrations of magnesium oxide range from 1 to 1.5%, the magnesium oxide may be present in the high-magnesium calcite and dolomite (see Section 3.5.6.a.4). That of strontium ranges from 400 to 1,600 p.p.m., and corresponds to the gypsum and aragonite present. The high strontium concentration (1,600 p.p.m.) is present in pit 13/46 where aragonite is present (18%) (see Section 3.5.6.a.4).

#### 4.1.5.F.e The Chemical Composition of the Sediments North of the Salt Pan (pit 13/47):

The concentrations of carbon dioxide decrease with depth from 25.4%

to 18.4% and this corresponds with the change in the proportion of carbonate minerals. The concentrations of calcium oxide also decrease from 37 to 33% and corresponds with the proportion of carbonate minerals and gypsum present. (Section 3.5.6.a.5). The concentrations of magnesium oxide in the sediments decrease with depth from 6.5 to 1.8%. The magnesium oxide values are high and the amounts of high-magnesium calcite and dolomite are not enough to explain these high values, so magnesite is probably present but was difficult to detect by the XRD technique, since its major peaks lie close to those of aragonite peaks. The concentration of strontium is generally more than 2,000 p.p.m. and corresponds to the aragonite present (Section 3.5.6.a.5).

#### 4.1.5.F.f The Chemical Composition of the Sediments of Sub-unit a:

The concentrations of carbon dioxide in the sediments range from 0.0 to 2.7%, indicating a low concentration of calcium carbonate minerals. The concentrations of calcium oxide range from 14.5 to 29.5% and corresponds with the gypsum and anhydrite present. The concentration of magnesium oxide ranges from 0.3 to 1.2%, and magnesite is probably present in small amounts. The concentration of strontium in the sediments ranges from 700 to 2,000 p.p.m. Such concentrations have been shown to be incorporated in the anhydrite and gypsum crystal lattices by Kinsman, 1964, and Butler, 1973. Also, a small amount of celestite may be present.

#### 4.1.5.F.g The Chemical Composition of the Sediments of Sub-unit b:

The concentration of carbon dioxide in the sediments ranges from 0.0 to 2.3%, thus indicating a low concentration of calcium carbonate minerals. The concentrations of calcium oxide range from 21 to 27.5% and correspond with the gypsum and anhydrite present. The concentrations of magnesium oxide range from 0.65 to 1.25%, magnesite may be present in a small amount. The concentrations of strontium range from 700 to 1,200 p.p.m. and may be incorporated in the anhydrite and gypsum crystal lattices.

#### 4.1.5.F.h The Chemical Composition of the Sediments of the Patterned Ground (pit 13/70):

The concentrations of carbon dioxide increase with depth from 12 to 14% and this corresponds with the change in proportion of carbonate minerals. The concentrations of calcium oxide also increase with depth from 16 to 24.5% and this corresponds with the proportion of

carbonate minerals and gypsum present. The concentration of magnesium oxide decreases with depth from 1.7 to 1%, the higher percentage near the surface is due to the presence of dolomite and heavy minerals, both decreasing in amount with depth. The concentrations of strontium increases with depth from 1,000 to more than 2,000 p.p.m. and corresponds to an increase in aragonite (Section 3.5.6.d).

#### 4.2 Groundwaters:

Due to the abundance of quartz and the absence of fine grained carbonates, reaction between the interstitial waters and the host sediments are minimal, and the formation of diagenetic minerals has mainly been by precipitation from concentrated interstitial waters. The diagenetic minerals consist mainly of gypsum, anhydrite, celestite and halite. The occurrence and distribution of these diagenetic minerals has been described in Chapter Three, and the chemical composition of the sediments has been described in the first part of this chapter.

In order to understand the processes which have formed and are in places still forming these diagenetic minerals, it is necessary to define the hydrologic regime and discuss the chemical analysis of the groundwaters. It is recommended that a survey of the sulphur isotopic composition of both brines and sediments be carried out in order to determine the relative importance of marine and continental sources of water as suppliers of sulphate into the southwestern coastal plain of Bahrain (Thode et al, 1961; Butler et al, 1973).

##### 4.2.1 Hydrology and Sources of the Groundwaters:

The southwest sabkha is mostly flat and low-lying; the surface elevations are generally slightly higher than A.H.W.M., apart from the salt pan (Mamlahat al Mumattalah) which lies at about 1m. below A.H.W.M. The surface of the water table usually lies 1.1m. below A.H.W.M. apart from the area of the accretion zone, where it lies just below A.H.W.M. Its depth from the surface ranges from 0.1m. in the salt pan to 1.7m. in the beach ridges in the area of profile I - II (see Appendix 4). So the water table surface slopes gradually from the shoreline towards the salt pan in a landward direction, suggesting that the groundwater flow is landwards.

In parts of the ridges and dunes, the surface sediments are dry, as the water table is at such a depth below the surface that the

potential height of rise of capillary water from the groundwater is below the ground surface (Fig. 4.9). In the area of the sabkha, salt pan, accretion zone and parts of the platform, the surface sediments are damp, as the potential height of rise of capillary water from the groundwater is above the ground surface (in Bahrain, the capillary rise is commonly between 1 and 1.5m. above the water table in sandy soils and it normally exceeds 2.0m. but is less than 3m. in loamy soils; Brunsden et al, 1980).

The level of the groundwater table fluctuates seasonally due to differing rates of evaporation; in summer, the evaporation rate is at its maximum and the level of the groundwater drops. Evaporation of waters in the capillary fringe leads to an increase in ionic concentration in the interstitial waters and finally to precipitation of some of the dissolved solids, the pore spaces, between the grains making up the sediments of the capillary fringe. In winter, the evaporation rate is at its minimum, and the level of the groundwater rises. In parts of the salt pan where the ground level is low, and the groundwater level is high, this may lead to a slight flooding of this part of the pan. This makes it possible for there to be sub-aqueous precipitation of gypsum on the surface of the sediments. Later the flood water is evaporated and salts, mainly halite, are precipitated.

The groundwaters of the southwest sabkha have a complex origin similar to those of other areas, eg, Abu Dhabi (Bush, 1973; Kinsman, 1964; Hsu and Schneider, 1973), Ranns of Kutch (Glennie and Evans, 1976), Libya (Sherif, 1978) and Egypt (Hassouba, 1980). As in these other areas, they appear to have originated by the mixing of seawater derived from the adjacent Gulf, with groundwater derived from the adjoining bedrock and with surface water either by direct precipitation and/or run-off. The following is a discussion of some possibilities of the origin of the groundwaters based on the observations of B.S.M.R.S., 1976, and comparison with similar areas, but further work is required to confirm this.

The groundwater of the sabkha is recharged laterally from the Gulf by 'flood recharge' and/or subsurface flow. 'Flood recharge' is a term suggested by Butler, 1969, as being descriptive of the process which rejuvenates older interstitial brines by the delivery at the

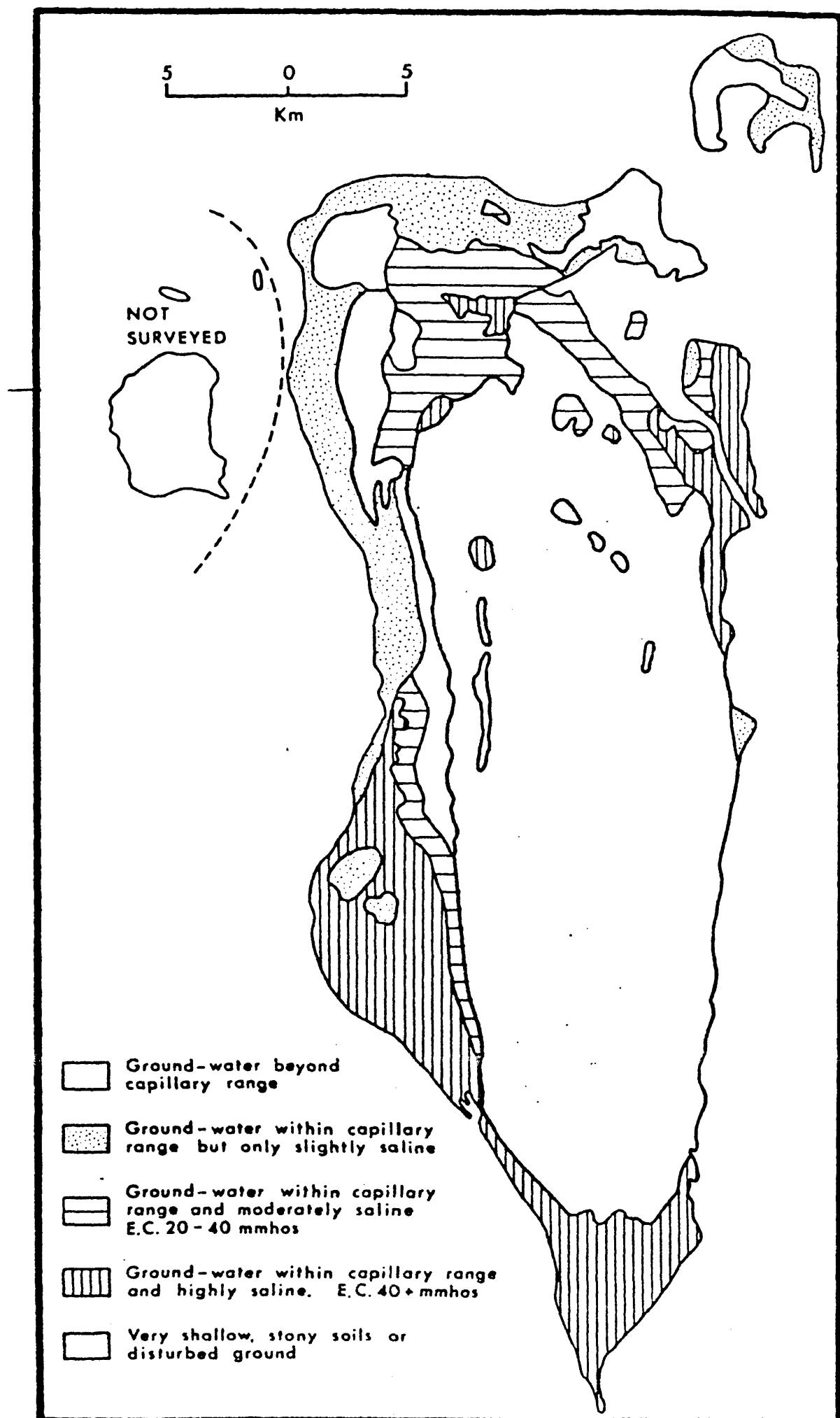


Fig. 4.9 The potential height of rise of capillary water from the ground-water, Bahrain (after B.S.M.R.S., 1976).

surface of seawater accompanied by downward soaking. In the southwest sabkha, flood recharge may occur in the areas which are not protected by the beach ridges (Fig. 4.10, line A"A', and Fig. 4.11.b). During storms marine inundation may cover vast areas (Fig. 4.10) and seawater may percolate downward and it may also evaporate. The importance of flooding in supratidal areas has also been recognised by Masson, 1955. Subsurface sea-water recharge may occur in the seaward margin protected by the beach ridges (line A A', Figs. 4.10, 4.11.a) and by both subsurface flow and flood recharge where there is an absence of ridges (line A"A', Fig. 4.10 and Fig. 4.11.b).

The possibility of seepage reflux as postulated by Adams and Rhodes, 1960, and supported by Deffeyes^e, Lucia and Weyl, 1965; and Murray, 1969, for the Isle of Bonaire, by Kinsman, 1969; and Bush, 1973, for Abu Dhabi, and by de Groot, 1973, for Qatar, whereby as the brine becomes more concentrated, further inland, it flows downward through the sediments on the way back to the sea, should be investigated (dolomitization of the sediments will be limited since there is a deficiency in fine grained aragonite in the area of study).

The continental groundwater is derived from the adjoining bedrock, mainly from Eocene aquifers (Brunsdon et al, 1980). The aquifers carry water originating in Saudi Arabia, supplemented by rainwater falling on the island, and contribute important quantities of sulphate and other ions to the surface water of Bahrain. The water table has been falling over a period of years and seawater encroachment is probably in progress due to increased artificial extraction from the aquifers (Wright, 1967). The importance of continental groundwaters as a source for the formation of evaporites has been emphasised by Sherif, 1978, for Libya. Also Brunsdon et al, 1980, note that during the various periods of emergence in the Eocene of Bahrain, penecontemporaneous dolomitization, and locally dedolomitization of the carbonate sediments occurred as a result of re-equilibration between the sediments and circulating fresh groundwaters, and the dedolomitization represents the maximum response to the influx of such groundwaters.

Meteoric waters reach the sabkha either by direct precipitation on the sabkha and/or surface run-off. In December 1974, heavy rainfall occurred totalling 41.6mm./day which is high by Bahraini standards, and was exceeded only twice in the previous ten years. B.S.M.R.S., 1976,

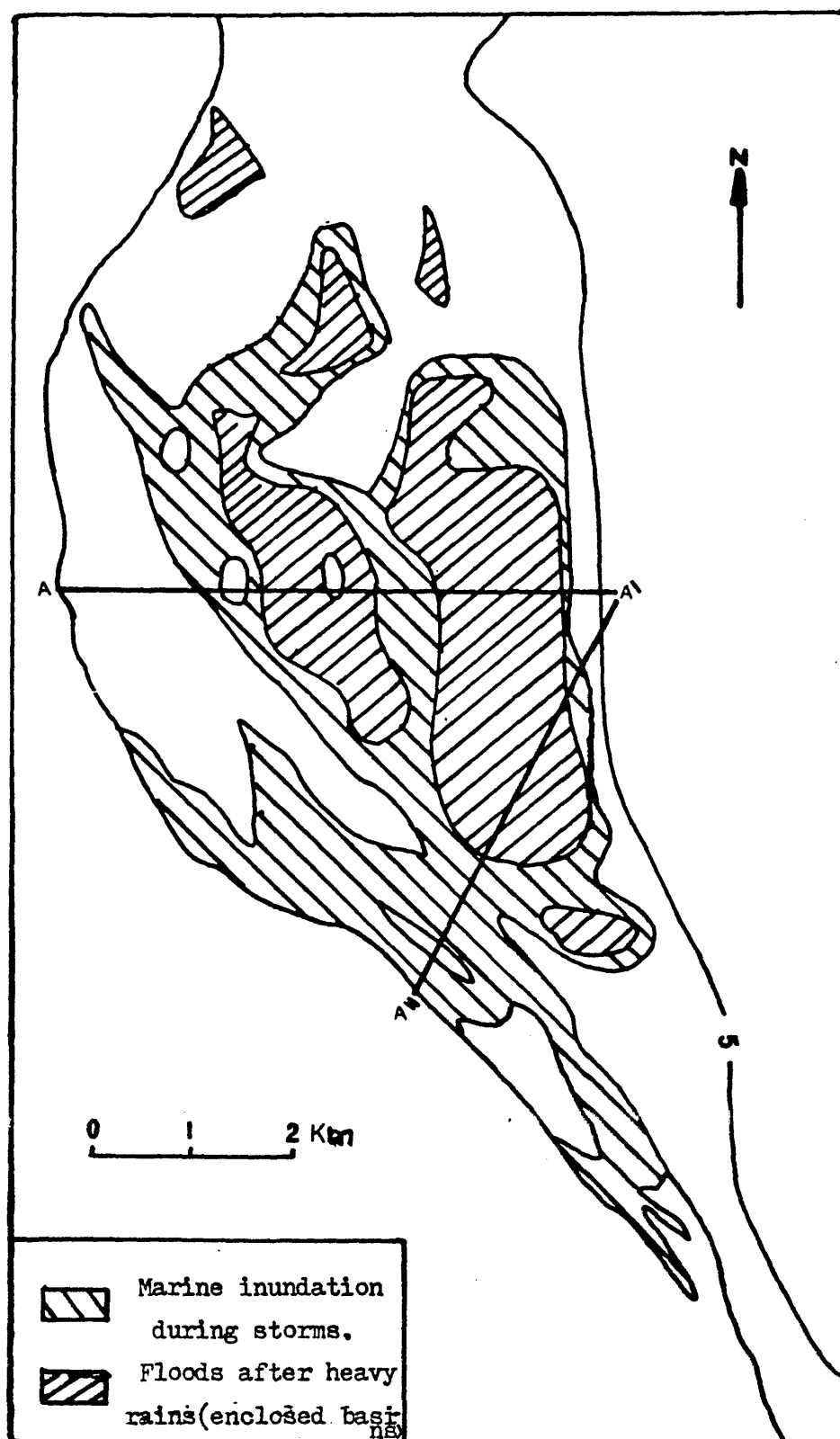


Fig. 4.10 Location of low areas subjected to flooding after storms, southwest sabkha (after B.S.M.R.S., 1976).

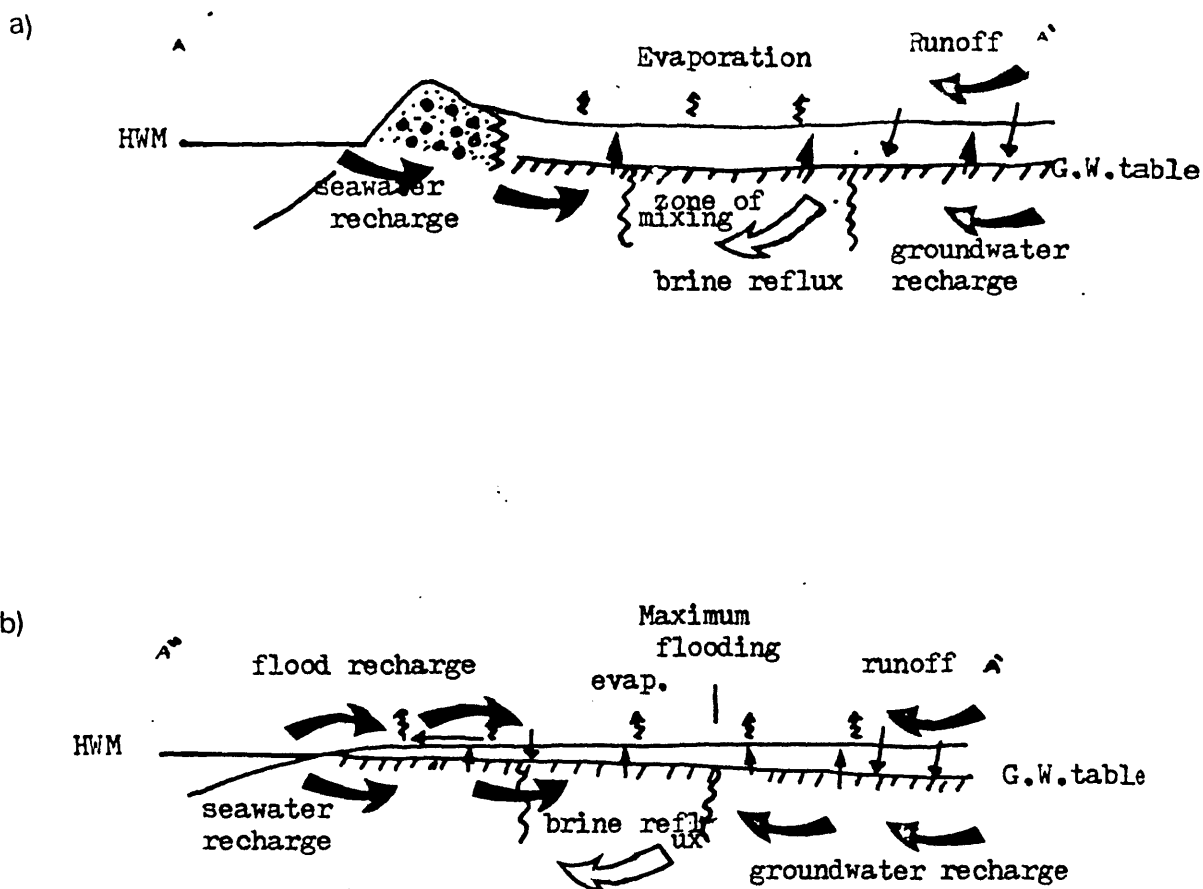


Fig. 4.11 Types of water supply in sabkhas, a) sabkha plain bordered by beach ridge. Water supply is by seawater recharge. b) Absence of beach ridge. Water supply is by seawater recharge, flood recharge and groundwater recharge (after Kendall, 1978).

note that it was difficult to observe the effects of this heavy rainfall on the sediments and watertable, as the sediments became very soft, and areas were discontinuously covered with shallow spreads of water thus making access impossible (see Fig. 4.10 for areas flooded after heavy rain storms). Surface run-off may reach the sea, percolate into the sabkha or return to the atmosphere by evaporation. In Bahrain, rain water contains a high amount of sulphate (Brunsden et al, 1980), which increases the sulphate content of the groundwater.

Dew contributes an important part of the groundwaters, particularly in dune areas, and its importance was noted by Bush (1973).

Two other mechanisms of water movement may contribute to the hydrodynamic processes; these are the 'capillary fringe' and 'evaporative pumping' mechanisms. The capillary upward movement of brines as proposed by Shinn et al, 1965, and supported by Friedman and Sanders, 1967, where through concentration of the pore solutions evaporitic minerals are crystallised at and below the water/air interface, and evaporation does not lower the groundwater table (then there is no apparent vertical hydraulic gradient under the groundwater table). The 'evaporative pumping' mechanism proposed by Hsu and Siegenthaler, 1969, where upward movement of subsurface waters is induced by a vertical hydraulic gradient under the evaporated area, and the outflow of the system is through evaporation into the air. The rate of pumping is not constant all over the sabkha, since the areas of deeper groundwater have lower concentrations of evaporites, because of more retarded evaporative loss, than areas with shallower groundwater.

These mechanisms are most likely to occur where the surface of the groundwater is very shallow and is therefore likely to be most important in the salt pan. Further investigations are required to establish which of the two mechanisms is dominant, though it is possible that both mechanisms may be operating.

#### 4.2.2 The Chemistry of the Groundwaters:

The groundwaters have been analysed for their major constituents; chloride, sulphate, sodium, potassium, calcium, magnesium and in some samples for strontium. The chemical analyses are tabulated in Appendix 4, and plotted in Figs. 4.12 to 4.19 as absolute concentrations in grammes/litre, as relative concentrations as compared with the con-

centration of the same elements in standard seawater (hereafter referred to as X.S.S.W.), and as the ratios  $Mg/Cl$ ,  $Mg/K$ ,  $Ca/Cl$ , and  $Mg/Ca$ , against the distance from the shoreline, and with reference to the major physiographic units.

The composition of standard seawater as absolute concentrations (gms/l) is given below:

	Salinity	Cl	SO ₄	Na	K	Ca	Mg	Sr
gms/l	35.85	19.84	2.78	11.02	0.409	0.422	1.32	0.0072

In the Gulf of Bahrain, there is a north to south increase in chlorinity, but chlorinities to the east of Bahrain Island are lower than chlorinities to the west. The chlorinity of the Gulf water adjacent to the southwest sabkha averages 30 - 31‰, and is far higher than the remainder of the Persian Gulf (Sugden, 1963), but is similar to mid-lagoon conditions at Abu Dhabi (Evans and Bush, 1969). Weather and seasonal variations lead to chlorinity fluctuations.

In the following section, the chemistry of the groundwaters will be discussed.

#### 4.2.2.A Calcium:

According to Usiglio in Clarke, 1924, calcium is the first cation to be removed from seawater during its evaporation in the form of calcium carbonate and then calcium sulphate (see also Levy, 1977; Borchert and Muir, 1964). Figs. 4.15 and 4.16 show that the concentration of calcium gradually increases landward away from the sea, until pits 13/60 and 15/28 after which the concentration gradually decreases towards the salt pan. In the salt pan, the concentration of calcium decreases from west to east (Figs. 4.13 and 4.15) and from south to north (Fig. 4.16). Along profile I - II, the concentration of calcium gradually increases landwards until pit 11/25 where calcium reaches a maximum of 2.1 gms/l, and then it gradually decreases until pit 11/28 after which it remains relatively constant (Fig. 4.12). The calcium/chloride ratio is inverse to the concentration of calcium, thus suggesting that where the concentration of calcium increases and the calcium/chloride ratio decreases, that calcium is being extracted in some form. On the other hand, where the concentration of calcium decreases and the calcium/chloride ratio increases, dilution of the brine and precipitation may occur; this is apparent from the decrease in the concentration of chloride and other cations (Figs. 4.12, 4.15 and 4.16). The dilution

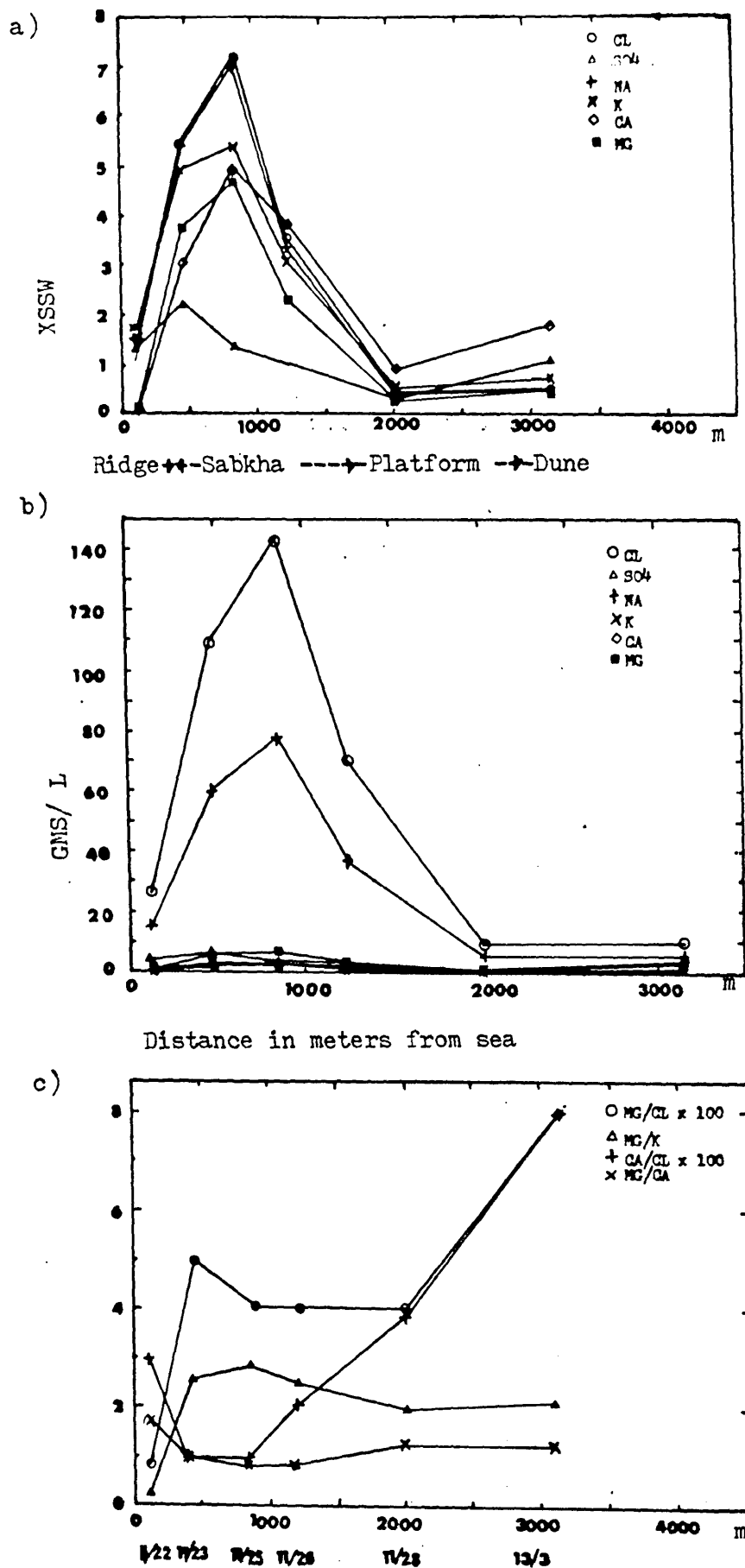


Fig. 4.12. Concentration of major elements of the ground waters along traverse I-II as; a) ratios to standard seawater, b) Gms/ L and c) ratios.

* In Figs. 4,12 to 4,19 the geomorphic units will be below a, the distances will be below b and the pit numbers will be below c.

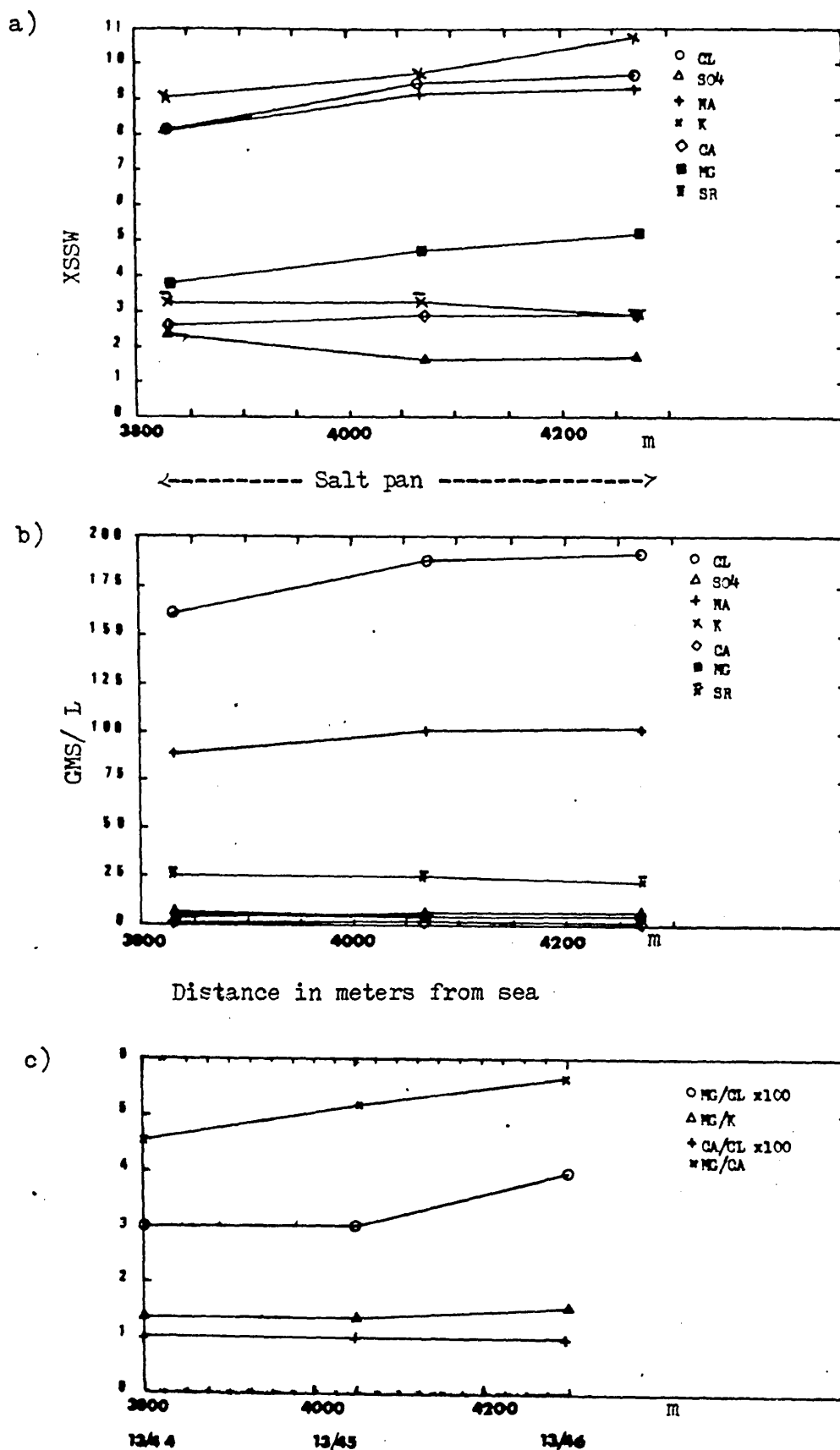


Fig. 4.13. Concentration of major elements and strontium of the groundwaters along traverse III-IV, as; a) ratios to standard seawater, b) Gms/L and c) ratios.

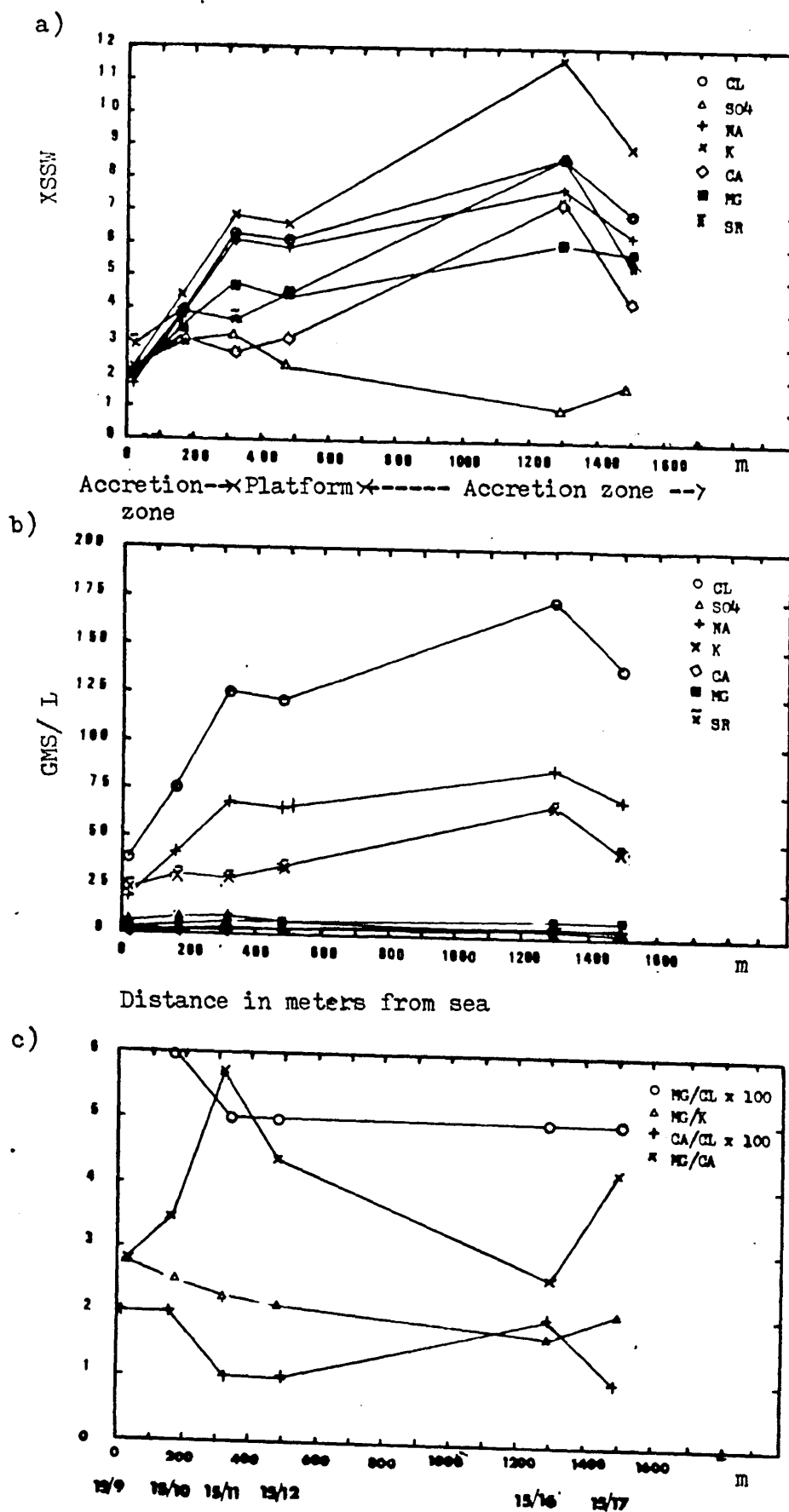
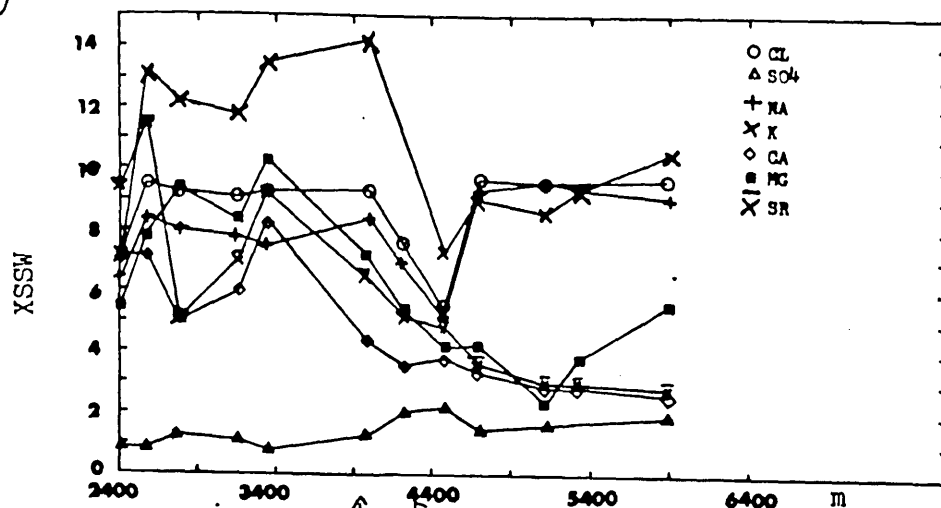
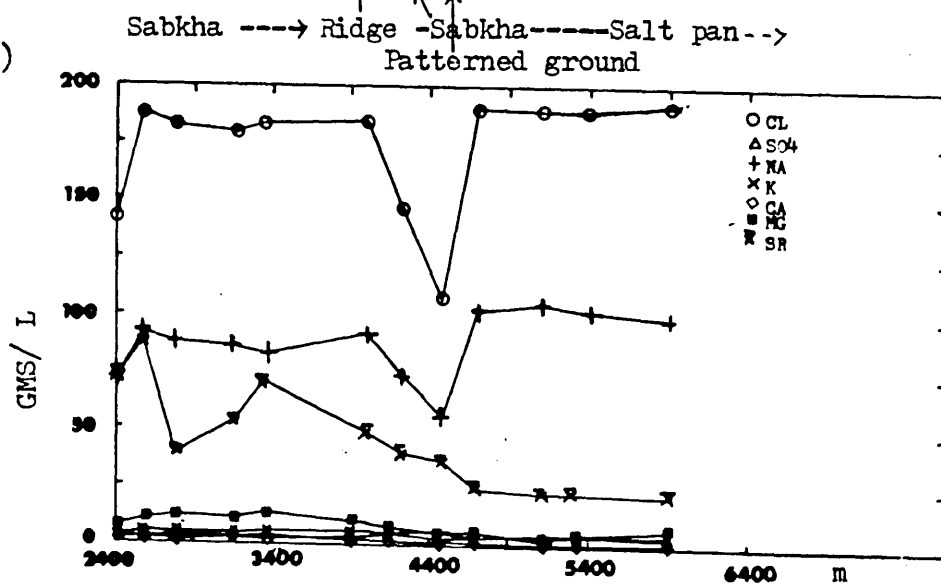


Fig. 4.14. Concentration of major elements and strontium of the groundwaters along traverse V-VI, as; a) ratios to standard seawater, b) Gms/L and c) ratios.

a)



b)



Distance in meters from pit 13/ 38

c)

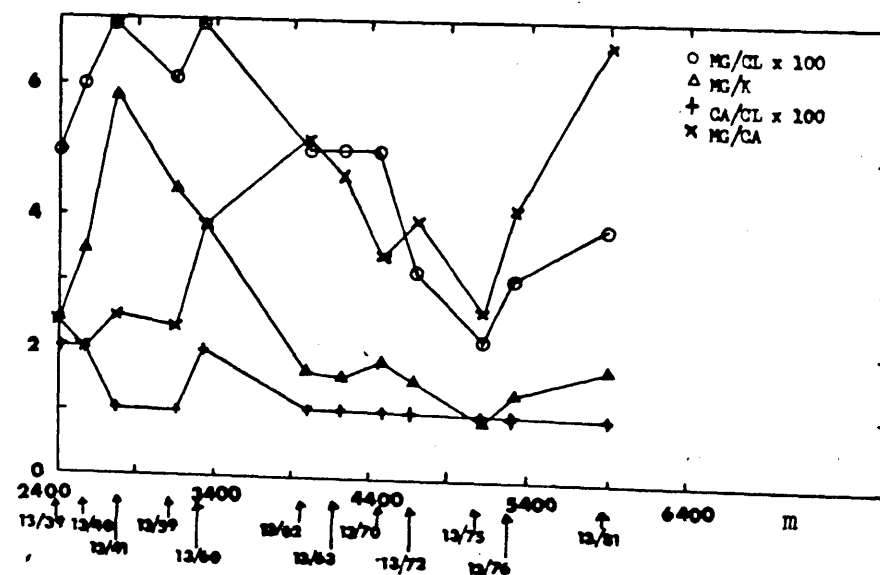
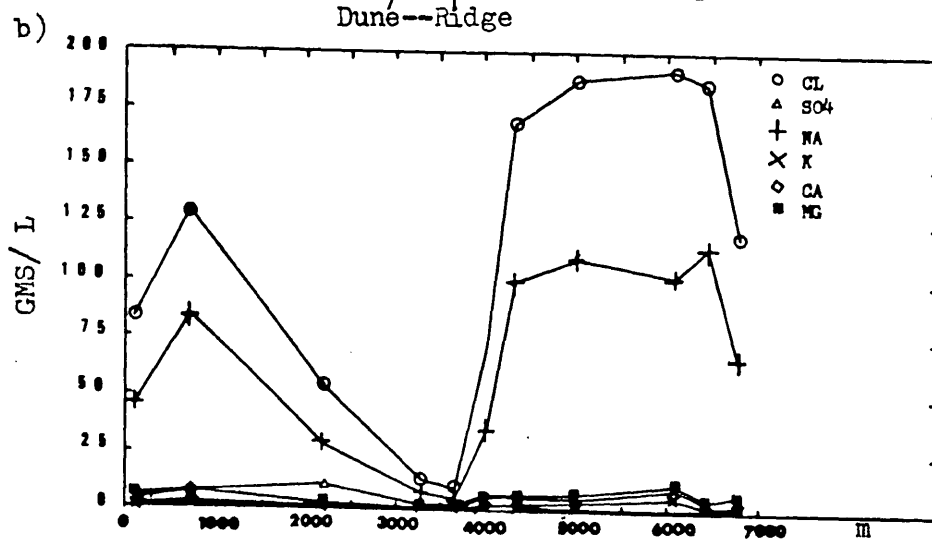
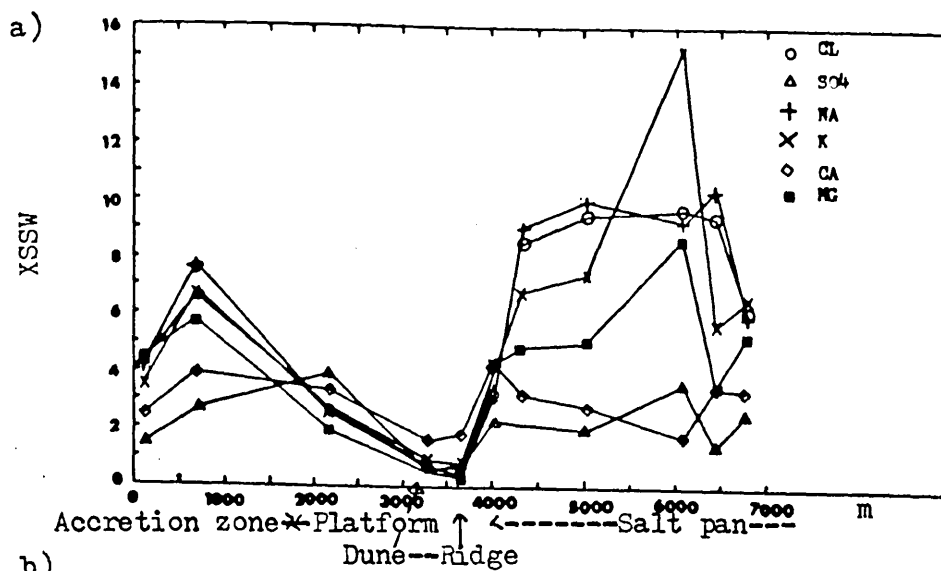


Fig. 4.15. Concentration of major elements and strontium of the groundwaters along traverse VII-VIII, as; a) ratios to standard seawater, b) Gms/ L and c) ratios.



Distance in meters from sea.

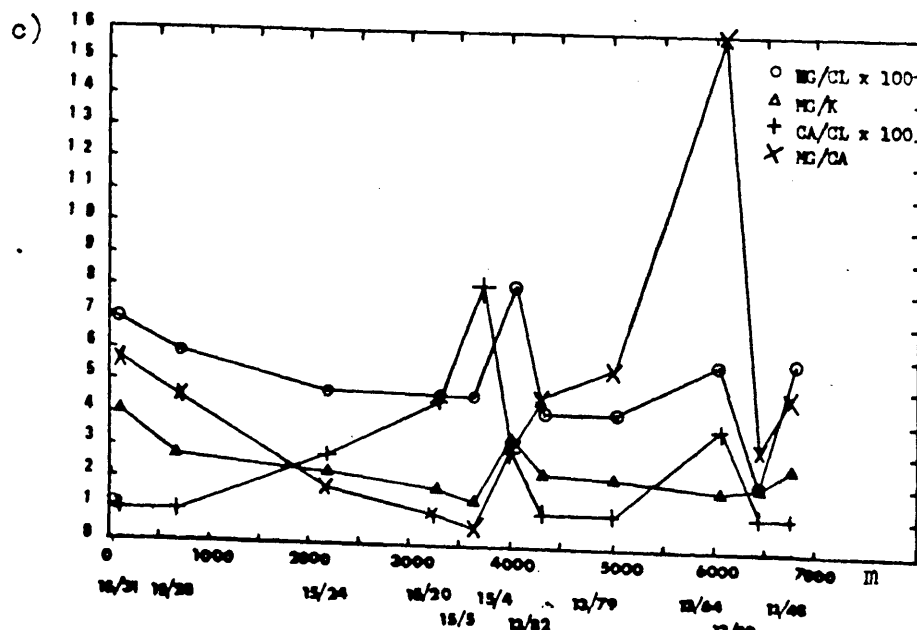


Fig. 4.16. Concentration of major elements of the groundwaters along traverse IX-X, as; a) ratios to standard seawater, b) Gms/ L and c) ratios.

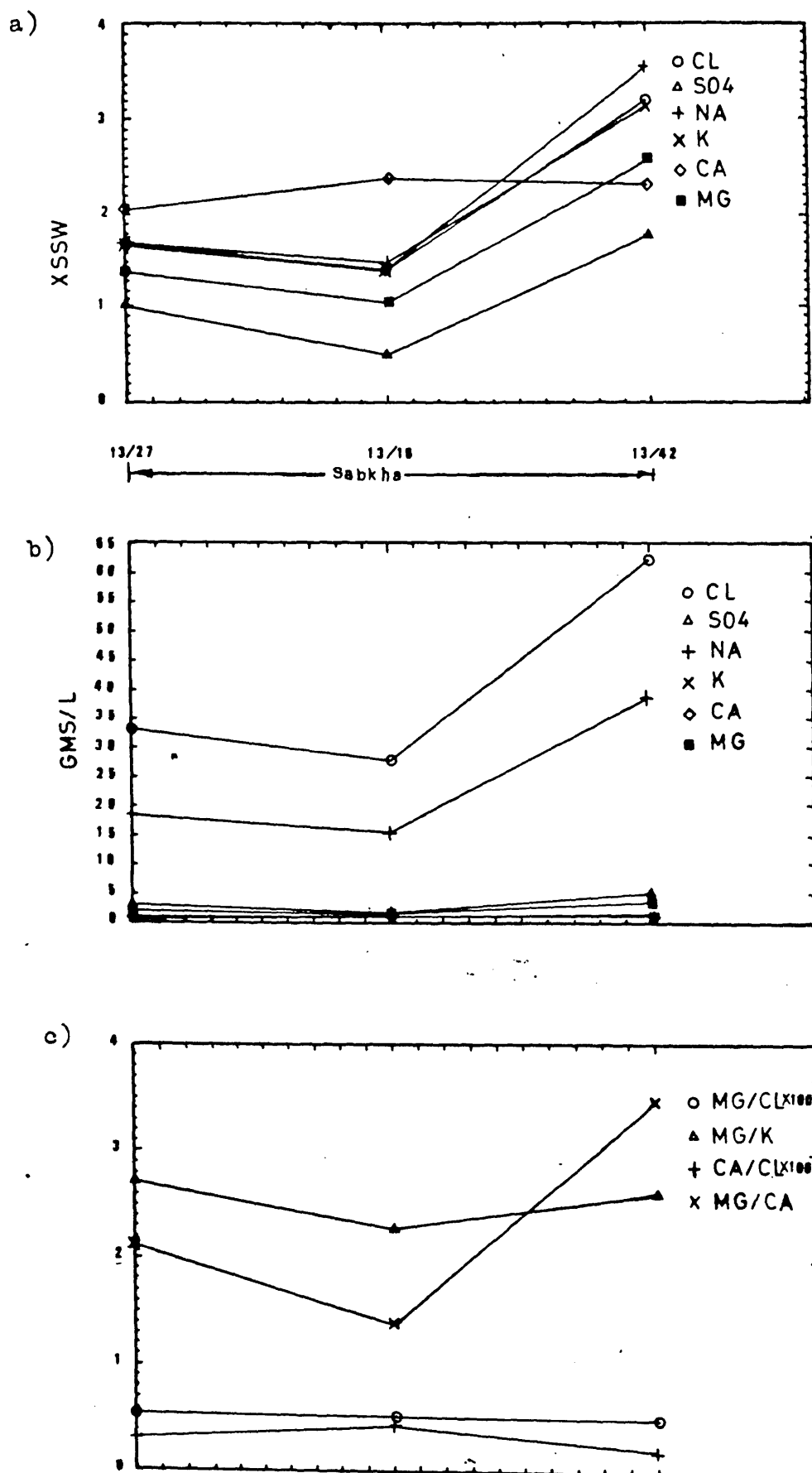


Fig. 4.17. Concentration of major elements of the groundwaters in pits 13/ 27, 13/ 16 and 13/ 42 in the sabkha, as; a) ratios to standard seawater, b) Gms/ L and c) ratios.

Note there are no distances as the pits are scattered in the sabkha for locations see Fig, 3,89.

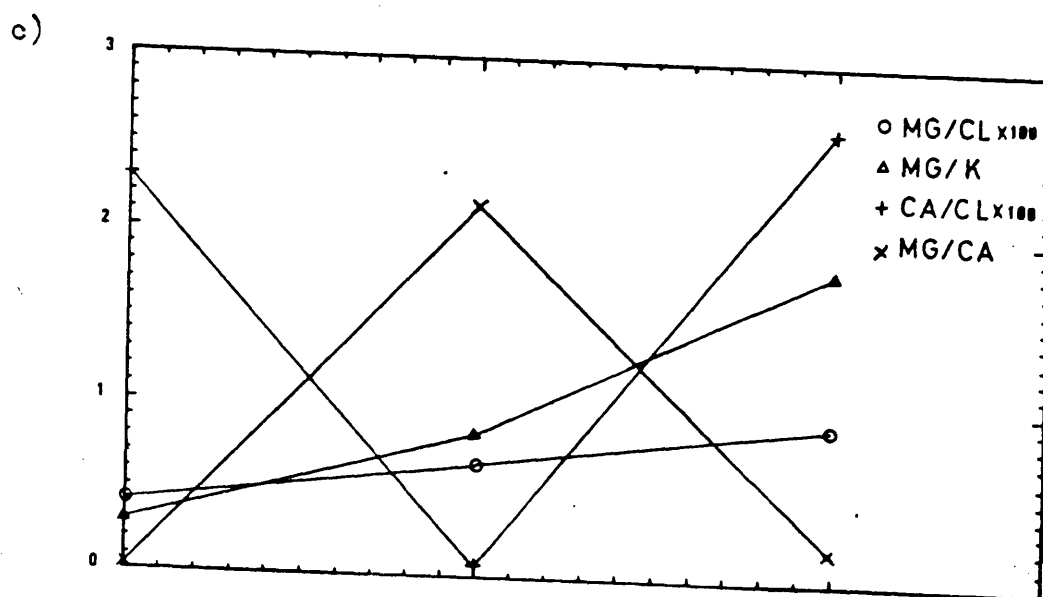
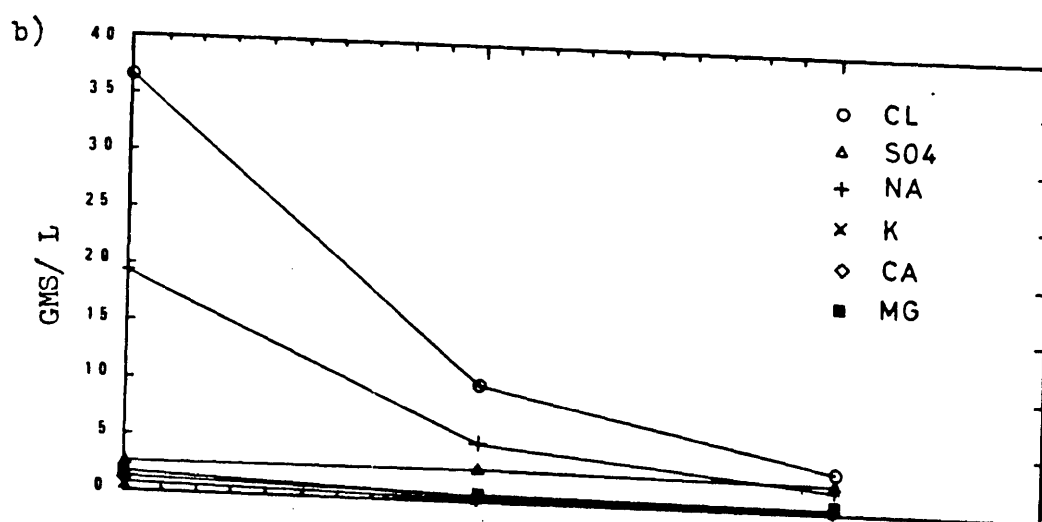
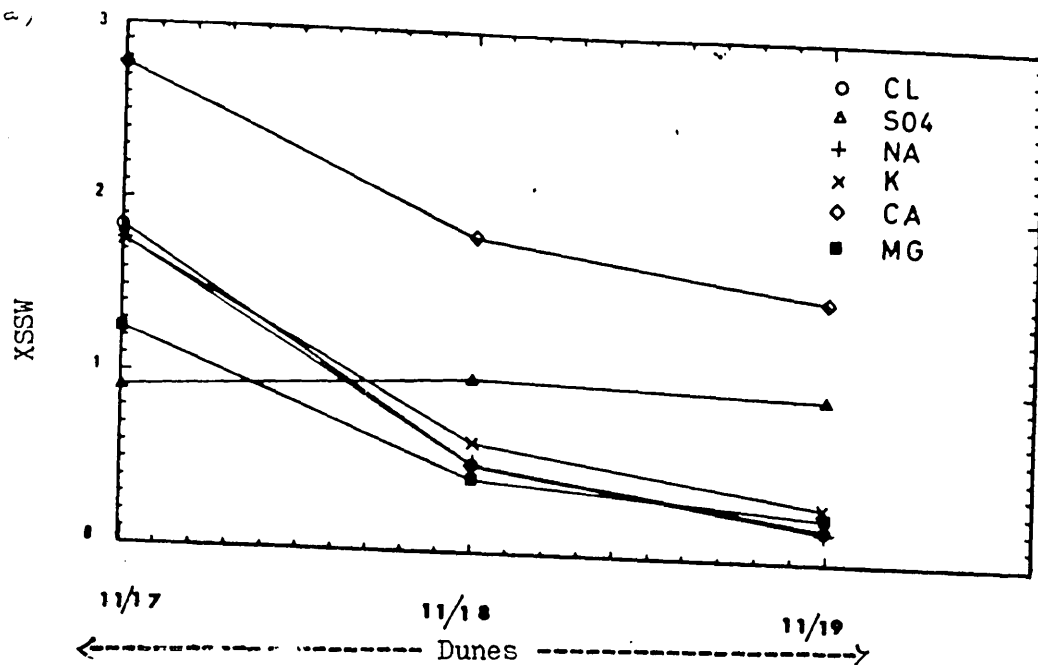


Fig. 4.18. Concentration of major elements of the groundwaters in pits 11/17, 11/18 and 11/19 north of the area of study (for locations see Fig. 3.89), as, a) ratios to standard seawater, b) Gms/L and c) ratios.

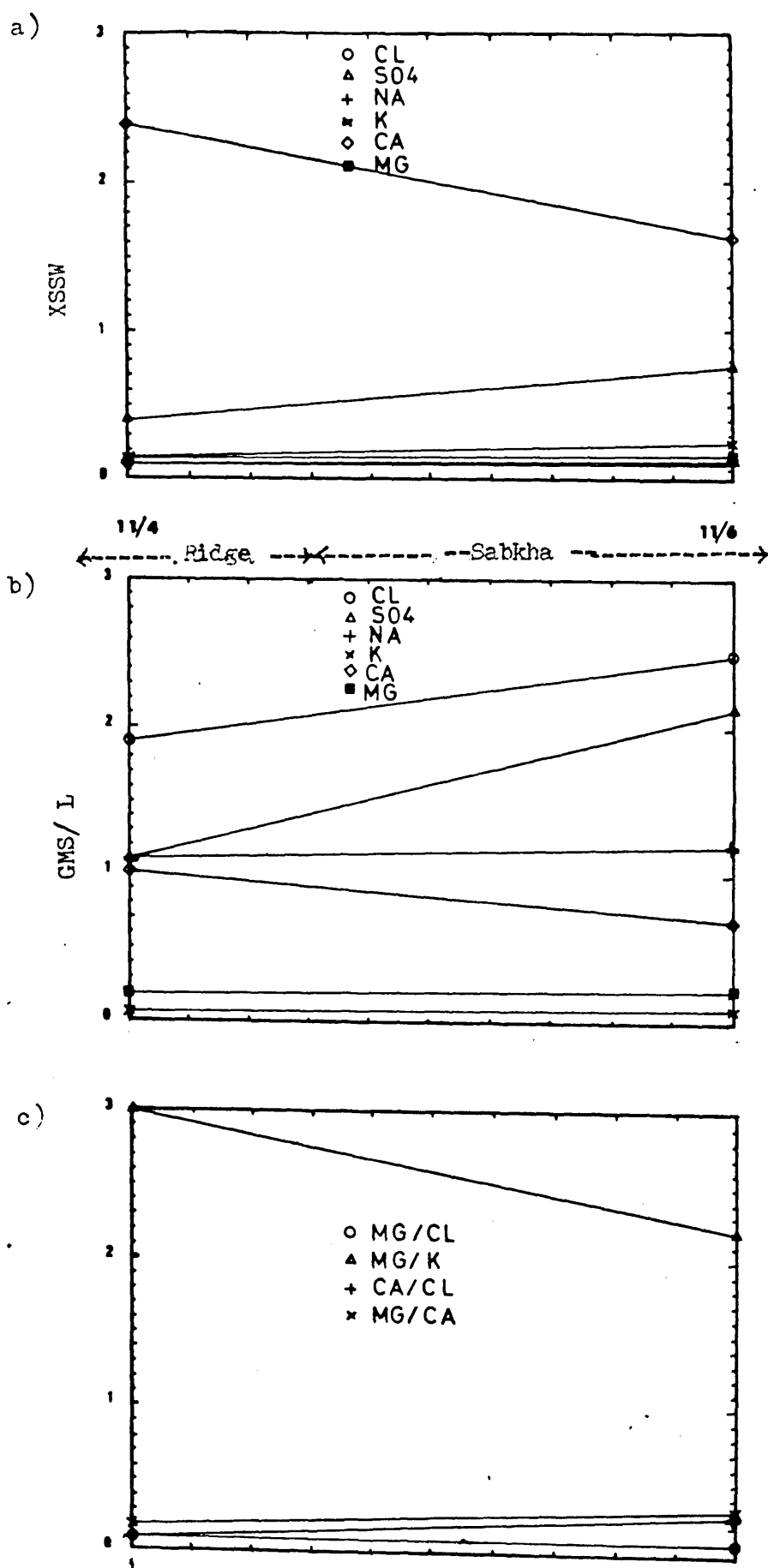


Fig. 4.19. Concentration of major elements of the groundwaters in pits 11/4 and 11/ 6 north of the area of study ( for locations see Fig. 3.89 ), as ; a) ratios to standard seawater, b) Gms/ L and c) ratios.

may be due to the mixing of relatively fresh continental groundwaters with the marine waters. The effect of dilution is apparent to the east of profile I - II (Fig. 4.12) and north of the area of study (Figs. 4.13 and 4.19), where extremely low values of ionic concentrations are due to the abundance of the fresh groundwater (fresh continental groundwaters are reported north of the area of study by Brunnsden et al, 1980, see Fig. 4.9). In profile V -VI, the concentration of calcium gradually increases from the sea landwards to have a peak of 3.1 gms/l (7.4 X.S.S.W.) at pit 15/16 (Fig. 4.14) and further inland it drops to 1.8 gms/l (4.3 X.S.S.W.).

#### 4.2.2.B Sulphate:

The concentration of sulphate ions in the groundwaters is generally low in the area of study. In profile I - II, the concentration increases landwards to 6.25 gms/l (2.2 X.S.S.W.) in pit 11/23 and then gradually drops to 0.35 gms/l (0.3 X.S.S.W.) in pit 11/28 (Fig. 4.12) due to the precipitation of gypsum. Further inland it rises to 3 gms/l at pit 13/3 probably due to dilution with sulphate-rich continental groundwaters. In profile VII - VIII (Fig. 4.15) the concentration of sulphate ions is generally low and fluctuates, having a rise in pit 13/70 (the patterned ground) to 6.1 gms/l. In the salt pan, profile III - IV, the concentration of sulphate drops slightly from 6.5 gms/l in pit 13/44 to 4.7 gms/l in pit 13/46 (Fig. 4.13), this is due to the interstitial precipitation of gypsum, some of the sulphate is probably reduced by bacterial action to form sulphide, where gas bubbles and the smell of  $H_2S$  have been recorded in pit 13/52 (Fig. 3.51) by B.S.M.R.S. (1976) while in profile VII - VIII there is a gradual increase from 4 gms/l in pit 13/72 to 5.4 gms/l in pit 13/81 (Fig. 4.15). There is also a gradual increase in concentration from pit 15/4, south of the pan, to pit 13/48, north of the pan. In the accretion zone there is a gradual increase landwards until pits 15/11 and 15/24 after which there is a fall in the concentration of sulphate towards the salt pan, where gypsum has precipitated and is found as discoidal crystals and anedral gypsum grains.

#### 4.2.2.C Magnesium:

In profile I - II, Fig. 4.12, the concentration of magnesium in the groundwaters gradually increases landwards to 6.2 gms/l (4.7 X.S.S.W.) in pit 11/25 and then drops to 0.63 gms/l further inland (Fig. 4.12). In profile VII - VIII the concentration increases landwards to 13.6 gms/l

in pit 13/60 and then gradually drops towards the salt pan (Fig. 4.15). In profile III - IV, in the salt pan, the concentration of magnesium gradually increases from west to east from 5 to 6.8 gms/l (Fig. 4.13). In profile VII - VIII, in the pan (Fig. 4.15), the concentration drops to 3.1 gms/l in pit 13/75 and then gradually increases towards the north to 11.5 gms/l in pit 13/64 and then drops sharply to 4.6 gms/l in pit 13/50 and increases again to 7 gms/l in pit 13/48. In profile V - VI magnesium concentration gradually increases in an inland direction but at pit 15/12 it drops slightly (Fig. 4.14). In profile IX - X (Fig. 4.16) magnesium concentrations increase until pit 15/28 after which it decreases in the direction of the salt pan. The magnesium/chloride and the magnesium/potassium ratios generally show similar trends (Figs. 4.12 to 4.16) and their increase and decrease can be explained by concentration as a result of evaporation and dilution by fresh water input respectively.

#### 4.2.2.D Strontium:

The concentrations of strontium range from 0.022 to 0.088 gms/l. The concentration of strontium in the groundwaters generally follows a similar trend to the concentration of calcium (Figs. 4.13, 4.14 and 4.15). The concentration of strontium in the groundwaters relative to its concentration in seawater is always higher than the concentration of calcium in the groundwaters relative to its concentration in seawater (see Appendix 4). This may be the result of both concentration of strontium by evaporation and the release of strontium by the dissolution of aragonite grains. Another factor is that calcium is removed from the water at an earlier stage than strontium.

#### 4.2.2.E Potassium, Sodium and Chloride:

The concentrations of potassium, sodium and chloride in the groundwaters generally follow similar trends (Figs. 4.12 to 4.19 and Appendix 4). In profile I - II (Fig. 4.12) the concentrations increase landwards until pit 11/25 where the concentrations of sodium and chloride are 7.2 X.S.S.W. and potassium is 5.4 X.S.S.W. Then they decrease in pit 11/28 to 0.5 X.S.S.W. and remain low after that (Fig. 4.12). This is probably due to dilution by fresh water influx. In profile VII - VIII (Fig. 4.15) the concentrations of sodium, potassium and chloride are higher than in profile I - II, and that for potassium fluctuates round 13 X.S.S.W. until it drops to 7.3 X.S.S.W. in pit 13/70, that for sodium fluctuates round 7 X.S.S.W. until it drops to 5.1 X.S.S.W.

in pit 13/70, while that for chloride fluctuates round 9 X.S.S.W. until it drops to 5.4 X.S.S.W. in pit 13/70 (Fig. 4.15). In the salt pan (Figs. 4.13, 4.15 and 4.16) the concentrations of sodium, potassium and chloride generally have a plateau at 9 X.S.S.W. (saturated solution of sodium chloride). In the accretion zone (Fig. 4.14) there is a gradual increase until pit 15/16 where the concentrations of potassium, sodium and chloride are 11.7, 7.8 and 8.7 respectively, after which they drop slightly. While in profile IX - X the concentrations of sodium, chloride and potassium increase until pit 15/28 having a peak of 7.7, 6.6 and 6.7 respectively in pit 15/5 (Fig. 4.14). Generally, the increase in ionic concentration of the elements is due to concentration by evaporation, while the decrease in ionic concentration is due to dilution by fresh continental groundwaters, since there is no precipitation of their salts.

#### 4.3 The diagenetic History of the Sediments:

The sediment distribution, types and mineralogy have been discussed in Chapter Three, while the chemistry of the sediments has been discussed in Section 4.1, and the hydrology and chemistry of the groundwaters have been discussed in Section 4.2.1 and 4.2.2. The following section will deal with the diagenetic history of the sediments.

Diagenesis is a general term and here it is restricted to the mineralogical, textural and geochemical changes that have taken place under low temperature and pressure after the deposition of the sediments.

##### 4.3.1 Aragonite and Calcite:

The aragonite and calcite present in the sediments are mainly primary sedimentary minerals in the form of whole skeletons, skeletal fragments and peloids. They are generally abundant in the surface sediments of the beach ridges, accretion zone and platform especially in profile I - II. The occurrence of unaltered foraminiferal tests accounts for the small amounts of high-magnesium calcite present.

The concentration of the groundwaters leads to the removal of calcium as aragonite since the temperatures are well above 30°C and the salinity is greater than 100‰ (Kinsman and Holland, 1969), but the small amount of aragonite precipitating is hard to detect as

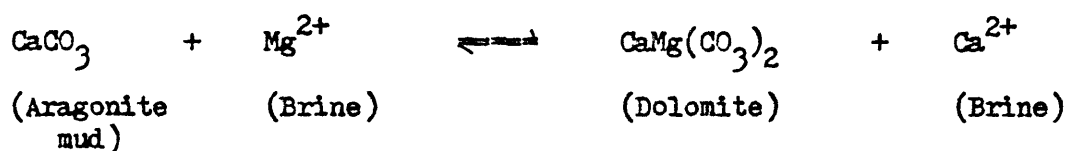
the surrounding sediments contain considerable amounts of skeletal aragonite.

The most obvious diagenetic feature observed in the carbonate minerals of these sediments is micritization; skeletal grains in the early stages of micritization are still identifiable as skeletal fragments, but grains in the more advanced stages are hard to identify. Kendall and Skipwith, 1969, working on sediments of Khor al Bazam, United Arab Emirates, and Taylor and Illing, 1969, working on sediments from Qatar, recognised the process of micritization, where skeletal grains are altered to aragonite micrite. The peloids exhibit a uniform micritized internal structure, similar to those described by Bathurst, 1971.

Some of the grains that were originally aragonitic have suffered a process of dissolution and reprecipitation which has resulted in them being altered to calcite. In some cases, the calcium carbonate released by solution of aragonitic grains has precipitated as an overgrowth on quartz and carbonate grains, especially at the ridges. Calcium carbonate was also deposited both as a calcite and aragonite cement due to oversaturation in the pore-waters produced by evaporation thus contributing to the slight cementation of the sediments making up the ridges.

#### 4.3.2 Dolomite:

The small amount of dolomite found in the sediments of the area of study is probably mainly detrital in origin. The detrital/dolomite probably consists of clasts of fine grained dolomitic limestones eroded from earlier Eocene dolomites, mixed with more distantly derived wind-blown material as suggested by Emery, 1956, who collected dust samples containing dolomite from the Arabian Gulf. The other source of dolomite albeit very limited is the diagenetic alteration of fine grained aragonite. According to Kinsman, 1964, Butler, 1971, and Bush, 1973, fine grained aragonite muds react with magnesium-rich brines having a high Mg/Ca ratio (more than 11) to produce dolomite according to the equation:

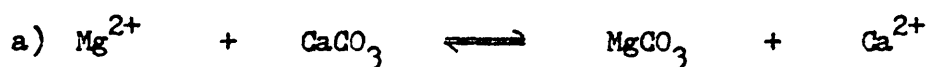


An average groundwater temperature of  $34^{\circ}\text{C}$  and small aragonite needles will be factors in increasing the rate of reaction. According to Hsu and Siegenthaler, 1969, the Mg/Ca ratio of the brine need not be particularly high to induce dolomitization and that a Mg/Ca ratio of more than 1 may induce dolomitization, the main factor being the rate of magnesium supply. In the southwest sabkha, dolomitization is limited since the host sediments mainly consist of quartz and coarse sand grade to gravel grade skeletal fragments. Only in the salt pan, pit 13/64, does the magnesium/calcium ratio reach 16 (Fig. 4.16), otherwise it is generally less than 6.

#### 4.3.3 Magnesite:

This magnesium carbonate mineral has been described by Kinsman, 1964, and Bush, 1973, and like the diagenetic dolomite is nearly always found in the less than 0.0625mm. fraction of the sediments. In the area of study magnesite is volumetrically insignificant, and has only been recorded in the surface sediments at pits 15/16 and 15/17 in profile V - VI.

Magnesite may be formed by one of two mechanisms, according to the equations:



In the first equation, magnesium-rich brines react with fine grained aragonite to produce magnesite and release calcium and strontium ions, while in the second equation dolomite is formed first and it reacts further to produce magnesite and hence dolomite and aragonite will both be absent. In the southwest sabkha since both aragonite and dolomite are present in the surface sediments with magnesite, then the reaction represented by either equation could produce magnesite. Magnesite is unstable with respect to dolomite and should the Mg/Ca ratio fall, then its place may be taken by dolomite.

#### 4.3.4 Celestite:

Celestite occurs dispersed in the sediments of the accretion zone

and platform, and within the sediments of the ridge in pit 15/15, where there is abundant aragonite. The dissolution of aragonite leads to the release of strontium which reacts with the sulphate present in the groundwaters to produce celestite. Also sulphate-rich waters may react with the strontium present in aragonite skeletal grains to produce replacive celestite (Hassouba, 1980). Strontium follows a similar trend to calcium and its decrease with calcium especially in the salt pan suggests the co-precipitation of celestite with that of gypsum and the mineral has indeed been found in association with gypsum (some of the strontium may be incorporated in the crystal lattice of gypsum as shown by Kinsman, 1964, and Butler 1973).

#### 4.3.5 Halite:

In the southwest sabkha, halite is an ephemeral mineral restricted to the near surface where it loosely cements the surface sediments of the salt pan and the low sabkha areas. Due to the high relative humidity of this area, it is unlikely that halite will form extensive deposits under natural conditions (Kinsman, 1976).

#### 4.3.6 Highly Soluble Evaporite Minerals:

None of the common highly soluble evaporite minerals have been recorded. Their formation in the near surface sediments is unlikely due to the high relative humidity of Bahrain (Kinsman, 1976).

#### 4.3.7 Gypsum and Anhydrite:

Several generations of gypsum are recorded in the sediments of the southwest sabkha; in Unit 2 gypsum nodules have been reported by B.S.M.R.S., 1976, in pits 13/43, 13/59, 13/63 and 13/42, lying above the water-table (the author could not detect these nodules in the material returned for analysis). Further work is required to establish the nature and origin of these nodules.

In Sub-unit 4d, discoidal gypsum crystals enclose some of the host sediments, but further inland the crystals are clear and are of the displacive type suggesting slow crystal growth (Kastner, 1970). This type of gypsum has been described from the Laguna Madre, Texas, by Masson, (1955) from the sabkha Faishakh by Illing et al (1965); from Abu Dhabi by Kinsman (1966); Bush (1973); and Shearman (1978); from Libya by Sherif (1978); and from Egypt by West et al (1979) and Hassouba (1980).

In the surface sediments of the sabkha, discoidal gypsum crystals are both poikilotopic and displacive, the displacive type is generally smaller in size and more abundant inland.

The surface sediments of the accretion zone contain several generations of gypsum and are very interesting. Seawards, gypsum is present as gravel grade displacive discoidal crystals. A bulky overgrowth has in some cases caused the crystals to become mis-shapen. The large size and clear nature of the crystals generally suggests that they have grown slowly. Few of the crystals found in this environment poikilotopically enclose sediments. Further inland, these discoids are absent and nodules of gypsum appear together with a very few cleavage plates of clear gypsum. The cleavage plates are probably derived from the gypsified Eocene sediments. Further inland nodular anhydrite and gypsum start to appear. The anhydrite nodules are formed of small laths, but are overlain by a layer which contains anhydrite as individual platy laths which are up to 1mm. in length and are similar to those described by Shearman, 1978. Gypsum crystals are discoidal and clear in the lower parts with the anhydrite nodules (approx. 100mm. deep) becoming poikilotopic towards the surface. Gypsum also occurs as nodules which are composed of discoidal gypsum clustered together, and in small amounts as short selenite habit crystals, rods and cleavage plates. Further inland anhydrite is absent and gypsum is present mainly as nodules and discoids with a very few cleavage plates. Still further inland, close to the Tertiary backslope, gypsum is mainly present as nodules. These nodules are composed of slightly cloudy to clear discoids which have a layer of nodules in between them of a different gypsum habit; the gypsum is mainly present as gravel to coarse sand grade needles and rods which are mis-shapen and welded together by an overgrowth of gypsum. A certain amount of etching has also occurred.

The discoidal gypsum appearing in the surface sediments of the accretion zone as individual crystals or nodular groups is developed in environments of high salinity and high sulphate content (Cuff, 1972; Bush, 1973). Calcium and sulphate ions become saturated as they rise by capillarity from the water-table to the surface, and gypsum precipitates in the form of discoidal crystals. When crystallization is fast, the poikilotopic type which encloses some of the host sediments is formed, while with slower crystallization and crystal

growth the displacive type which is clear is formed. These discoids grow together to form nodules (primary gypsum nodules have been reported by West et al, 1979, from Egypt). The anhydrite nodules which are present with the gypsum discoids have, at least in part, a gypsum precursor. When the pore water is concentrated and the stability field of anhydrite is reached (Hardie, 1967), then some gypsum will go into solution and anhydrite will form. Anhydrite is not found further inland of pit 15/16 as the concentration of the groundwaters is reduced. The presence of these more dilute groundwaters is supported by the presence of nodules of gypsum which are formed of needles and rods. This form of gypsum is precipitated when the groundwaters are less concentrated, in this case due to the mixing with continental groundwater.

The surface sediments of the platform also contain gypsum discoids in the seaward parts and these again pass into nodules inland. No anhydrite was recorded in the sediments of the platform.

The sediments of the dunes are generally rich in wind-abraded gypsum crystals, small nodules of anhydrite sometimes also exist. Similar concentrations of wind-blown gypsum concentrations have been reported from Abu Dhabi by Kinsman, 1966.

The sediments of the pan are very interesting, since they have anhydrite nodules and gypsum crystals in many habits. Generally the vertical sedimentary sequence in the pan from bottom to top is a) anhydrite, b) gypsum needles, c) displacive gypsum discoids, and d) gypseous quartz arenite, the gypsum being thin discoids and different habits of needles. South of the pan, the sequence varies slightly; a) gypsum needles and anhydrite nodules, b) anhydrite and gypsum needles changing laterally to gypsum needles, c) displacive gypsum discoids (this unit is absent to the east), and d) gypseous quartz arenite.

Gypsum freely precipitating from saline waters in brine pans normally occurs as needles and rods. Similar subaqueous gypsum has been described by Schreiber, 1978. Evaporation and concentration of the water in the pan until complete dryness occurred. This led to the formation of different habits of gypsum needles, which probably precipitated at different stages of concentration. These are: long

needles with six crystal faces, long needles with four crystal faces, rods, short selenite-like crystals and crystals which look like discoids but with well-developed faces. North and west of the pan, the groundwater concentration and temperature became well into the anhydrite stability field and some of the gypsum dehydrated to anhydrite. The salt pan was later covered with terrigenous sediments within which discoidal gypsum was precipitated. The presence of a few needles at the surface may be explained by flooding of the surface and sub-aqueous precipitation of these needles.

Hemihydrate has been recorded by X.R.D. in the sediments of Sub-units a and c in the south-west of the salt pan. Kinsman, 1966, has recorded this in the upper 20 - 30mm. of the sediments in areas of extremely high temperatures where dehydration of gypsum to bassanite but not to anhydrite may occur. But as these samples generally came from below the top 20 - 30mm. this explanation seems unlikely.

#### 4.3.8 Conclusion:

From the previous discussion, it is evident that in a quartz-rich sabkha the brine produced by evaporation contains high concentrations of sodium, magnesium, potassium and chloride and is depleted in calcium, sulphate and strontium. The lack of carbonate mud has also led to the evolution of this type of brine. As, for example, the more sheltered Abu Dhabi lagoons allowed more carbonate mud to be deposited, which upon reaction with magnesium-rich groundwaters allowed more diagenetic activity, represented by dolomitization and the release of calcium some of which reacted with the sulphate present in the brine and the precipitation of gypsum. The brines of such a sabkha where carbonate mud is abundant would be depleted in magnesium and sulphate and enriched in calcium and chloride.

According to Shearman, 1966, such brines as those of the area of study would be capable of producing the theoretical suite of bitterns carrying magnesium (at the present time it is unlikely to happen in the southwest sabkha due to high relative humidity, but should the relative humidity level change in the future, this process may be likely to occur).

According to Bush, 1973, the present distribution of minerals in the sabkha plain, especially the distribution of diagenetic minerals,

may not be the distribution which is at present in equilibrium with the groundwaters. This is important since it is unreasonable to try to explain the whole of the present distribution of diagenetic minerals by reference to the present groundwaters, and when a study of ancient coastal sabkhas of considerable extent is carried out it must be remembered that the minerals found in these ancient sabkhas are the result of many diagenetic changes, some of which occurred at an early stage and some at a later stage.

## CHAPTER FIVE

### Geological History

In the preceding chapters of this thesis the geomorphology of the southwest coastal sabkha of Bahrain, together with the nature and chemistry of the sediments and groundwaters of that sabkha have been discussed. This information together with radio-carbon dates determined for the sediments of the beach ridges (Table 5.1 and Fig. 5.1 for locations) make it possible to outline the evolution of that part of the southwest coastal plain of Bahrain (Fig. 5.2).

The history of the evolution of the coastal plain of Bahrain has been outlined by Brunsden et al, 1980, and the work of this thesis is a further development of that work.

The dolomites and limestones of the Tertiary escarpment, landwards of the sabkha, are the oldest sediments which crop out in the area of study. Apart from scattered outcrops of Quaternary limestone there is little evidence of the Quaternary transgressions and regressions, which have produced deposits in other parts of the coastal plain, in this area. This lack of exposure of earlier Quaternary deposits may be due to subsequent marine erosion and/or deflation, or more likely to burial beneath younger sediments (shallow drilling is required to confirm this).

During the Würm glaciation (70,000 to 17,000 years B.P. according to Fairbridge, 1961) continental conditions prevailed over almost the whole of the Arabian Gulf, during which times Bahrain Island stood as a rocky protuberance surrounded by the aeolian sands of the Arabian desert. Aeolian activity played an important role at this time, as it transported the sand and heaped it against the upstanding backslope of this rocky protuberance, and probably on top of the Quaternary limestone (Fig. 5.2.1). The main wind of that period, as it is today, was the "Shamal" wind (N and W.NW) as reported by Glennie, 1970, and as is evident from the barchan dunefields and the deflated remnants of dunes in Bahrain which show SW inclined cross stratified bedding. The distribution of sand by this wind resulted in the sediments around the rocky protuberance having an asymmetric shape, with wide plains and the formation of dunes on the west, and narrow plains on the east.

The sediments of Unit 1, the light brownish grey, moderately well sorted, medium quartz arenite represent the early stages of dune

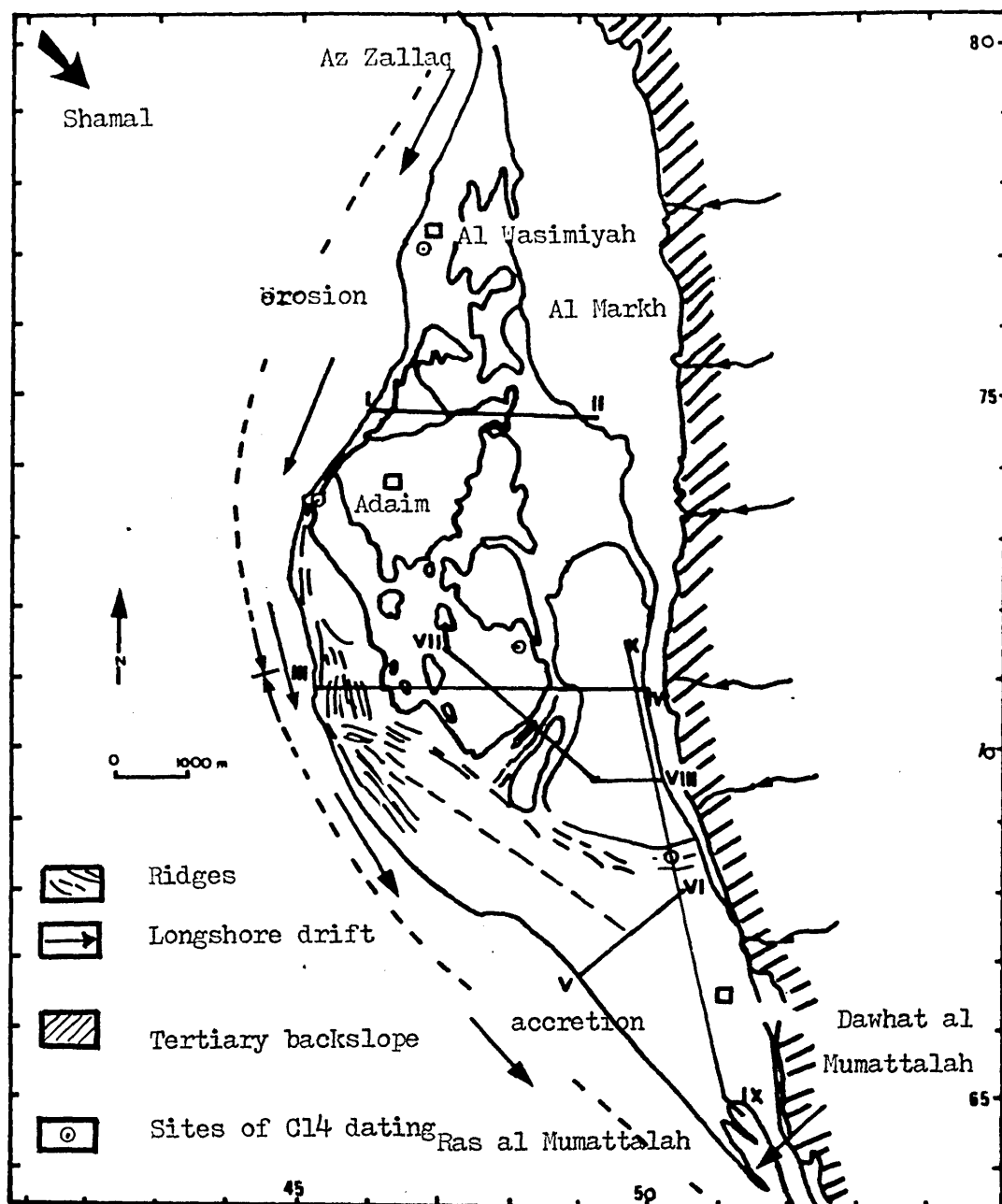


Fig. 5. I. Southwest sabkha, sites of C14 dating.

Table 5. I.

Radiocarbon ages of selected beach ridge and sabkha sediments, Southwest sabkha

Location (grid ref.)	Environment	Sample description	Height AAD (m)	Age (Years B.P.)
457737	Beach ridge	Cerithid gastropods	2.3	4900 $\pm$ 150 4740 $\pm$ 160
475773	"	"	3.0	4230 $\pm$ 140 4340 $\pm$ 150
505682	"	"	2.0	3130 $\pm$ 130 3330 $\pm$ 180
481716	Sabkha	"	2.0	4470 $\pm$ 110 4570 $\pm$ 120

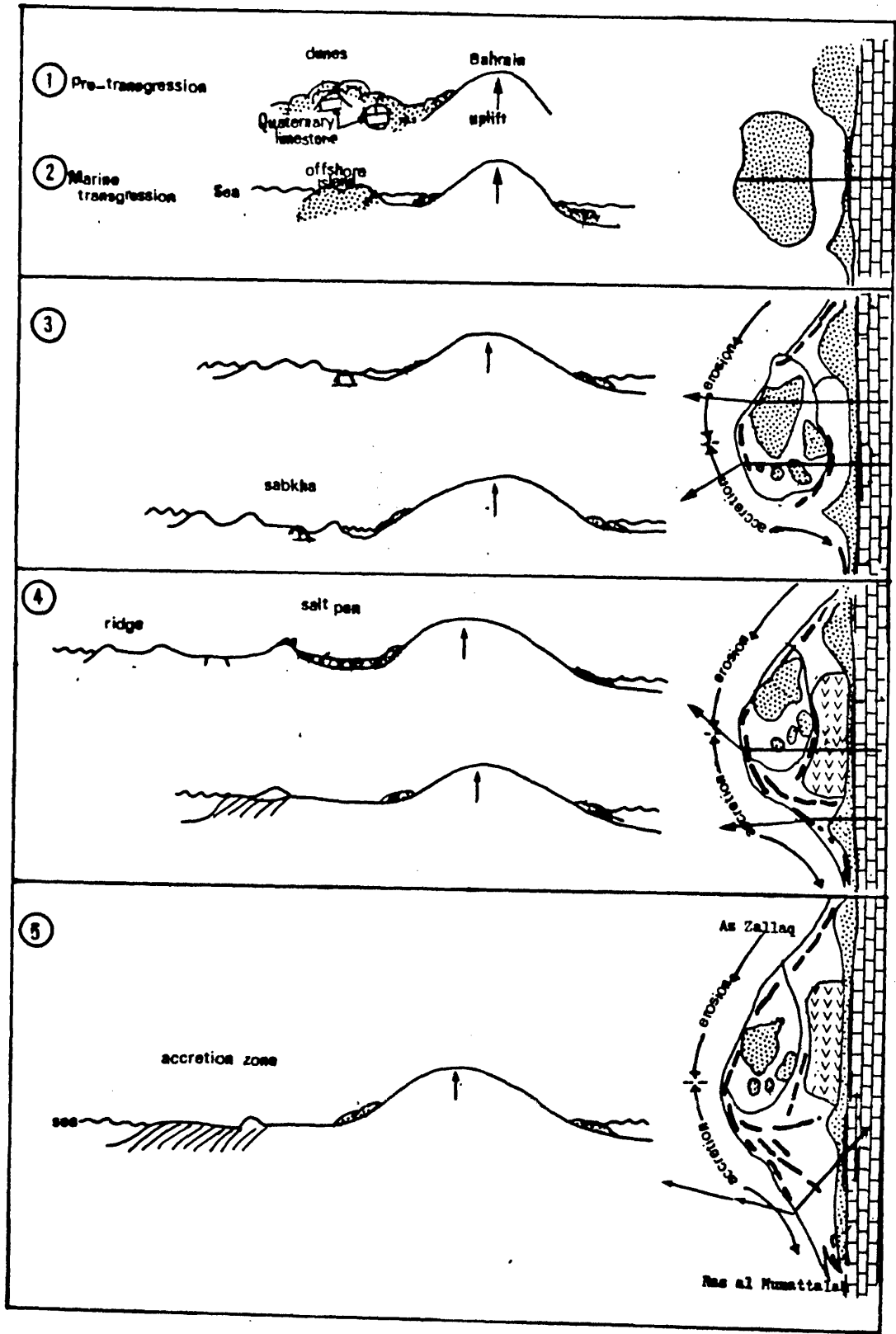


Fig. 5.2. Sketch of the evolution of the southwest coastal plain of Bahrain.

formation, The moderately good sorting, the presence of feldspars, quartz and poly-crystalline quartz grains, and the general roundness and frosted nature of the quartz grains confirm that this is an aeolian unit (according to Glennie, 1970, the combination of the previously mentioned factors suggest an aeolian origin for sediments). The presence of carbonate grains which consist of aragonites, high-magnesium calcite and retain their original structure and mineralogy

in the sediments of Unit 1 in profile I - II suggest that there has been restricted fresh water influx. The chemistry of the groundwater in pits 11/28 and 13/3 (Fig. 4.12) shows however that dilution due to fresh water influx is occurring at the present time, so the carbonate grains are not now in equilibrium with the groundwaters. Alteration of the carbonate grains by dissolution/reprecipitation has begun. The sediments of Unit 1 in profile VII - VIII contain no aragonite and less carbonate minerals (5 - 8%) than those in profile I - II, because the sediments were protected from the transgressing sea, as they lay below the sediments of Unit 2.

The sediments of Unit 2 form the main bodies of the dunes and are found in the interdune areas; these consist of yellowish orange, moderately well sorted fine to medium quartz arenites. The sediments are loose, laminated, have a low silt plus clay content and have high angles of dip and suggest deposition in an aeolian environment. This is supported by the presence at the present time of deflated dunes with sediments similar to those of Unit 2. There are two types of quartz in these sediments; fine to medium grains and medium to coarse grains which are probably derived from two different sources. Unit 2 differs from Unit 1 in that there is a change of colour, better sorting, an increase in the quartz content and a decrease in the content of carbonate mineral grains with an absence of aragonite and a notable decrease in the number of molluscan skeletal fragments.

During the Flandrian transgression, the low lying desert dunes of Arabia were drowned and the Gulfs of Bahrain and Salwa were formed thus leading to the isolation of Bahrain (according to Kassler, 1973, the date of the last dune migration across the Gulf of Salwa would be approximately 7,000 to 8,000 years B.P.). A. J. Keij and G. R. Varney (reported in Kassler, 1973) state that the recent carbonate sediments of the Gulf of Salwa are underlaid by uncemented quartz sands. These uncemented quartz sands are probably similar to the

sediments described as Unit 2 in this thesis.

The drowning of the coastal plain of Bahrain is best documented on the east coast of Bahrain at Ra's Hayyan, where shells collected from a beach ridge deposit overlying truncated dune sands gave  $C_{14}$  ages of between 6,330 and 6,940  $\pm$  120 years B.P. (Brunsden et al, 1980, and Fig. 5.1). A similar remnant but undated feature is found on the westerly flanks of the backslope near the southern end of the southwest sabkha (Brunsden et al, 1980).

Only the higher dunes which were probably built around the Quaternary limestones in the southwest sabkha, which at present have heights of up to 6.0m. AHD and may have been higher in the past, may have remained unsubmerged, forming a small offshore island (Fig. 5.2.2).

Wind played a different role; on the land areas, a process of deflation started, while on the coast and shallow marine areas the wind produced waves and littoral currents which eroded sediments and transported them from the north to the south. The effects of these processes have been very important in the evolution of the coastal plain. The deflation process is discussed later.

As a result of the marine transgression, a shallow marine strait developed between the unsubmerged dunes and the main island (Fig. 5.2.2) similar to that which exists between Umm Na'san and the main island today. In the north of this marine strait deposition of Sub-unit 3a, pink^{ish} yellowish gray, poorly sorted, bimodal (gravel grade to coarse sand and medium to fine sand) quartzose skeletal calcarenite, occurred due to the mixing of locally produced carbonate grains with reworked dune sands which were transported from the north by littoral currents. The environment in which the sediments of Sub-unit 3a were deposited was a restricted marine one as the fauna consists of a large number of individuals of a few species. The northern part of this strait was slightly deeper than the southern part as is confirmed by the presence of more fossiliferous sediments and less silt plus clay (1 - 7% in the sediments of Sub-unit 3a in profile I - II and up to 46% in those in profile IX - X). The carbonate grains contain a high percentage of aragonite (48 - 65%) and high-magnesium calcite (8 - 10%) thus they were obviously not subjected to an influx of fresh water. In the north the top of the unit is cemented by an acicular

aragonite cement characteristic of intertidal cementation, (Bathurst, 1971), thus suggesting shoaling north of the strait. This is confirmed by the presence of an algal peat both in the north and south of the marine strait.

The sediments of Sub-unit 3a are easily distinguishable from those of Units 1 and 2 which were deposited under continental conditions and contain abundant wind-abraded quartz, while those of Sub-unit 3a contain abundant carbonates and were deposited under shallow marine conditions.

The sediments of Sub-unit 4a, very pale orange, moderately to poorly sorted, medium to fine slightly quartzose skeletal pelletal calcarenite were deposited on top of the sediments of Sub-unit 3a. The pellets are characteristic of sheltered, possibly intertidal sedimentation. South of the marine strait the sediments of Sub-unit 4a contain 20% quartz due to the mixing of the pellets with reworked dune sand transported from the north. The sediments of Sub-unit 4a are distinguishable from those of Sub-unit 3a in that they contain more pellets and have a higher carbonate minerals percentage.

Both the sediments of Sub-units 3a and 4a represent stages of progradation of the coastline and hence a marine regression. Their deposition led to the sealing of the north end of the marine strait changing it to a marine inlet, and connecting the offshore island to the main island (Fig. 5.2.3).

Wave action played an important role by planating the low lying dunes and the small outcrops of Quaternary limestone thus producing a wave-cut platform on the seaward side of the offshore island (Fig. 5.2.3). A combination of progradation and a slight fall in sea level led to the development of a veneer of cerithid gastropods on the surface sediments.

Quartz sand from the dunes in the north was transported to the south by littoral currents and mixed with locally produced carbonate grains, to be later deposited at the southwestern side of the offshore island and further south. This eventually led to further restriction of water movement in the marine inlet. The sediments of this phase of

sedimentation are represented by Sub-unit 3b, consisting of light grayish orange, poorly sorted, bimodal (gravel grade and medium to coarse sand grade) calcareous skeletal quartz arenite. The generally low silt plus clay percentage (less than 1%) indicates deposition under a high energy environment. The quartz grains are of two types and are possibly of two different origins; the coarse sand grade, frosted well-rounded quartz grains are similar to those present in the dunes, while the medium sand grade quartz grains are similar to those present in the sabkha. The carbonate grains are mainly skeletal fragments with their original texture and consist mainly of aragonite. These carbonate grains are probably produced locally and were not exposed to fresh water. The peloids and some skeletal fragments may have been transported from further north. Towards the sea, the quartz and carbonate grains have a carbonate coating due to the dissolution of some of the carbonate grains and later reprecipitation. Some of the carbonates in solution also reprecipitated as acicular aragonite cement (Fig. 3.14) which is characteristic of intertidal cementation (Bathurst, 1971). This unit can be distinguished from Sub-unit 3a in that it has more quartz and fewer carbonate grains.

Waves aided by wind led to the formation of beach ridges and the progradation of the coast further southwards (Fig. 5.2.4). Radiocarbon dates of cerithid gastropods from the sediments of the ridges near Ra's Nawmah (the crests of the ridges are at 2.3 - 3.0m. AHD) gave ages ranging from  $4,740 \pm 160$  to  $4,900 \pm 150$  years B.P. (Fig. 5.1 and Table 5.1), being younger in age further north, at Ra's Abu al Mawj, giving ages ranging from  $4,230 \pm 140$  to  $4,340 \pm 150$  B.P., still younger at the ridges in the south which when developed transformed the marine inlet to a lagoon, giving ages ranging from  $3,330 \pm 180$  to  $3,130 \pm 130$  (Fig. 5.1 and Table 5.1).

The sediments of Sub-unit 4b represent this stage of sedimentation and were generally deposited on top of Sub-unit 3b apart from in profile I - II where they were deposited on top of the sediments of Unit 2. The silt plus clay grade percentage is generally low suggesting a high energy environment of deposition. The quartz grains are of two types similar to those of Sub-unit 3b, and they also have a carbonate coating towards the sea. The carbonate grains are whole shells and skeletal fragments which are generally worn and show stages of dissolution and reprecipitation. The carbonate which has gone into

solution is the source for the coating on the quartz grains. Some of the carbonate grains are produced locally, while others which are worn and rounded have been transported from the north. Where Sub-unit 4b crops out at the surface it is covered with a shell lag which is blown from the local produced carbonate grains onto the ridges. In profile III - IV the sediments of Sub-unit 4b show that the percentage of carbonate minerals decreases and quartz increases in a landward direction. This is due to the limited ability of both wind and waves to carry the gravel grade carbonate grains further inland.

The main difference between the sediments of Sub-unit 3b and 4b is the absence of peloids in the sediments of Sub-unit 4b and an increase in the percentage of carbonate minerals.

Further littoral transport led to the build out of a wide accretionary plain (Figs. 5.2.4 and 5.2.5) composed of Sub-unit 4b with a lateral extension of Sub-unit 4c, composed of dark yellowish orange, moderately sorted, coarse to medium skeletal calcareous quartz arenite. The main differences between the sediments of Sub-units 4b and 4c are that those of the latter are laminated and not homogenous as are those of 4b, they are better sorted, contain more quartz and many fewer carbonate grains. The carbonate grains are mainly smaller skeletal fragments, worn and rounded and there is considerably less aragonite than in Sub-unit 4b. These factors suggest that littoral transport played a major role in supplying these mixed sediments and depositing them in the intertidal/subtidal zone.

A decrease in the amount of dune sand available for littoral transportation led to an increase in the production of carbonates and deposition of the sediments of Sub-unit 4d on top of those of Sub-unit 4c. The sediments of Sub-unit 4d consist of light orangish gray, poorly sorted calcilutite quartzose calcarenite. This unit was deposited in a low energy environment as it has a silt plus clay grade percentage of 30 to 50%, and is homogenous probably due to biologic activity. The carbonate grains are mainly peloids due to the activity of algae on carbonate grains. The carbonate grains are mainly aragonitic and thus no fresh water influx affected them.

A mechanism for the growth of the accretion zone can be seen operating today in the southern portion of the southwest sabkha at Ra's al Mumattalah. There, small embayments in which small algal flats have developed are being enclosed and with continued sedimentation are building up into supratidal flats. This process of continued progradation has led to the sealing of the lagoon and its transformation into a salt pan (Mamlahat al Mumattalah).

In the north of the salt pan, the sediments in pit 13/47 show evidence that the salt pan was at one stage a lagoon. The sediments in the pit consist of a calcarenite layer consisting of peloids some of which look like pellets, overlain by a pelletal calcarenite layer. These sediments represent the shore of the lagoon and there is probably carbonate muds below the sediments of the pan. The opening between the ridges south of the pan was probably the inlet of the lagoon. When the lagoon was sealed, an increase in the ionic concentration of the water led to the subaqueous precipitation of gypsum as needles and rods. The groundwater concentration and temperature fell into the anhydrite stability field and some of the gypsum has dehydrated to anhydrite. The surface of the pan was infilled by wind-blown sediments and sediments derived from the adjacent back-slope. The groundwaters became more dilute due to the mixing with continental groundwaters. At a later stage concentration of the interstitial waters led to the precipitation of discoidal gypsum. The surface of the pan was probably not completely filled with wind-blown sediments because the area immediately upwind, to the northwest, is covered by a protective coarse lag of cerithid shells and thus does not yield much sand for transportation to the salt pan (Brunsden et al, 1980).

The early diagenesis of the sediments of the coastal complex started as soon as the sediments were deposited. Evaporation of water from the interstitial waters led to the increase of the ionic concentration and the precipitation of aragonite and gypsum. Wind also had a very important effect on the areas inland of the immediate vicinity of the coast of the former offshore island and the dunes fringing the main island, early in the history of the evolution. Deflation stripped the cerithid-rich surface sediments off the wave planated surface and exposed the sediments of Unit 2, thus forming the sabkha geomorphic unit and exposing the large gypsum crystals

growing near the surface. Smaller gypsum crystals have been moved south by the wind to mix with the sediments of the accretion zone, the sand dunes and the dune sands fringing the main island. Sometimes rounded wind-blown gypsum crystals occur capping the dunes (e.g. pits 13/38 and 15/6, see Fig. 3.47).

Even today, the scale of deflation in this area is impressive, as many thousands of cubic metres of sand have been swept southwards under the action of the "Shamal" (N) winds to add to the southward extending accretionary plain. A measure of the efficacy of this process can be obtained by the fact that pits which were up to 1.5m. deep excavated in the accretion zone in December 1974, were completely obliterated by April 1975 (Brunsden et al, 1980). Deflation is not effective in removing sediments from the salt pan as the water table is shallow and as a result the surface is damp.

Patterned grounds have been reported around the margins of the salt pan, producing well-developed structures on the western side of the pan, and polygons on the northern side of the pan (Brunsden et al, 1980). Patterned grounds in deserts are commonly associated with wetting and drying as well as with salt crystallization (Hunt and Washburn, 1966). Important factors in the formation of patterned grounds are the type of sediments and the climatic and hydrologic variables. These variables include the frequency of wetting and drying, the depth of the water table, the relative importance of surface and capillary water, the nature of the groundwater and the nature of temperature changes.

In the salt pan in the southwest sabkha, the patterned grounds are produced by the sideways and upwards migration of sulphate-rich capillary waters which precipitate gypsum by evaporation. Further crystallization of gypsum results in expansion and up-heaval of the enclosed sediments. In pit 13/70, west of the salt pan, the surface sediments of the patterned ground are weakly cemented by gypsum which poikilotopically encloses the grains of the host sediments.

Beach ridges are being cliffed at the northwestern side of the southwest sabkha as a result of erosion of the coastline in that area. This, combined with littoral transportation of the eroded sediments to the south means that with time all the sediments that

make up the southwest sabkha will migrate in that direction leading to the southward progradation of the coast.

The present day geomorphology and sedimentary sequence of the southwest sabkha is a result of a series of events initiated by the drowning of the low lying coastal desert dunes of Arabia during the Flandrian transgression, followed by reworking, redistribution and mixing with locally produced carbonates leading to southward progradation of the coastline and hence a regression. The sediments of Units 1 and 2 represent the desert dunes before the transgression. The sediments of Sub-units 3a and 4a represent the sediments deposited into the marine strait and the commencing of progradation of the coast in the north of the area of study. The sediments of Sub-units 3b, 4b, 4c and 4d represent a regressive cycle. In addition to those sub-units, diagenetic minerals have been developed in the surface sediments and the salt pan.

## CHAPTER SIX

### Summary and Conclusions

The southwest coastal plain of Bahrain covers an area of approximately 60Km². It is a low Quaternary coastal plain complex consisting of six geomorphic units, these are; beach ridges, sabkha, salt pan, accretion zone, platform and aeolian sands with dune form.

The climate of Bahrain is extremely arid, having high temperatures, low and variable rainfall, predominant northwesterly "Shamal" winds which are persistent and strong, fog and dew are common and potential evapotranspiration is high.

The present day physiography and pattern of sediments of the southwest coastal plain were developed by the following sequence of events. Continental condition prevailed over almost the whole of the Arabian Gulf during the Würm glaciation (70,000 to 17,000 years B.P.), Bahrain standing as a rocky protuberance surrounded by the aeolian sands of the Arabian desert. During the Flandrian transgression (approximately 7,000 years B.P.) sea level rose to approximately 4.5m. AHD, thus leading to the drowning of most of the low-lying desert dunes of Arabia, leaving some of the higher dunes, formed on a Quaternary limestone base, unsubmerged as small offshore islands. At this time, the transgressing sea entered the Gulfs of Bahrain and Salwa, thus isolating the rocky protuberance forming the main island of Bahrain from Arabia and preventing the continued supply of aeolian sand. In the study area, a small offshore island was formed when a marine strait developed between it and the main island. Deposition of locally produced carbonates mixed with reworked dune sands, led to the progradation of the coastline and sealing of the north end of the marine strait transforming it into a marine inlet and connecting the offshore island to the main island. Wave action planated the low lying dunes and the outcrops of Quaternary limestone, producing a wave-cut platform which was later veneered with cerithid gastropods, as a lag, due to combination of progradation and a slight fall in sea level. Further deposition of locally produced carbonates mixed with quartz sand from reworked submerged dunes carried south by littoral drift led to the southward progradation of the coastline and the formation of an accretion plain. Waves aided by wind led to the formation of beach ridges and the progradation of the coast further southwards. Further littoral transport led to the expansion of the accretion plain. This process of continued progradation led to the sealing of the marine inlet and its transformation into a lagoon.

At a later stage this lagoon was transformed into a salt pan.

As soon as the sediments of the coastal complex were deposited, the early diagenesis of the sediments started by the interstitial precipitation of aragonite and gypsum and alteration of the primary aragonitic sediments. Wind also played an important role inland where deflation removed the cerithid cover from the wave planated surface, in some areas exposing the underlying sediments and forming deflation windows. The final result of this process was to form the sabkha geomorphic unit. Deflation also removed the finer material from the surface sediments moving them southwards to mix with the sediments of the accretion zone or depositing them on top of the sand dunes and the dune sands fringing the main island. A rather late stage phenomenon was produced at the borders and in the north of the salt pan; the migration of sulphate-rich interstitial waters sideways and upwards as a result of evaporation has led to the formation of polygonal masses of gypsum giving rise to patterned grounds.

Erosion of beach ridges at the northwestern side of the sabkha, combined with littoral transportation of the sediments to the south, indicates that with time, the whole southwest sabkha will move southwards resulting in the southward progradation of the coast.

The sediments of Units 1 and 2 (quartz arenites) represent the desert dunes before the transgression. Sub-units 3a (quartzose skeletal calcarenite) and 4a (slightly quartzose skeletal pelletal calcarenite) represent the sediments of the marine strait. Sub-units 3b (calcareous skeletal quartz arenite), 4b, 4c (skeletal calcareous quartz arenite), and 4d (calcilutitic quartzose calcarenite) represent the sediments of a regressive cycle produced by progradation of the coastline. In addition to these units, diagenetic minerals have been produced in the surface sediments and the salt pan, due to concentration of groundwaters by evaporation.

The results of the chemical analysis of the sediments of the southwest coastal plain confirm and help explain the mineralogy of the sediments. It has been shown that the concentrations of the oxides and elements vary from one unit to the other thus corresponding with the change in the mineralogical composition and the proportion of each mineral. One of the interesting problems revealed by this analysis

is the presence in some of the units of high levels of magnesium oxide which cannot be accounted for by the presence of dolomite and high-magnesium calcite. Some of the possible sources of these high levels of magnesium oxide are; the presence of magnesite which may not be detected by the XRD technique if there is abundant aragonite, since its major XRD peaks lie close to those of some of the aragonite peaks, and the presence of magnesium bearing heavy minerals or clays, e.g. Hassouba, 1980. Hassouba and Shaw, 1980, have shown that in the sabkha west of Alexandria authigenic palygorskite is closely associated with the evaporative authigenic gypsum and appears to have precipitated with it from highly saline waters. As the samples were washed thoroughly before analysis another possible source may be the presence of an insoluble mineral phase, e.g. brucite ( $\text{Mg}(\text{OH})_2$ ), this possible additional source has been previously noted by Bush, 1973. Further work will have to be carried out in order to ascertain the source of this magnesium oxide.

Another interesting aspect of the chemical analysis of the sediments is the concentration of strontium. As previously mentioned, strontium is closely linked with the mineralogy, and its presence depends on the presence of aragonite and celestite, and to a less extent on the presence of gypsum and anhydrite (Kinsman, 1964; Butler, 1973). In some cases the concentration of strontium could not be accounted for by the mineralogy. A possible source is the presence of celestite which was not detected because all its major XRD peaks fall close to those of minerals that are abundant in the sediments and only very small amounts would be necessary to explain the strontium detected as 1,000 p.p.m. strontium is equivalent to 0.21% celestite. There is no reason why celestite should not be formed since both strontium and sulphate ions are present due to their concentration by evaporation. Further work on the geochemistry of strontium, similar to that of Butler, 1973, is recommended, because the concentration of strontium in sedimentary sulphates is dependent on the absence or the degree of dolomitization. The area of study is a good example of limited dolomitization and should reveal interesting results.

Another aspect is the concentrations of aluminium oxide, sodium oxide and potassium oxide. If they were present in feldspars, and assuming that these feldspars are sodic feldspars ( $\text{NaAlSi}_3\text{O}_8$  having a  $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$  ratio of 0.608) and potash feldspars ( $\text{KAlSi}_3\text{O}_8$  having a

$K_2O/Al_2O_3$  ratio of 0.924), then  $(K_2O+Na_2O)/Al_2O_3 = 1.532$ . This ratio does not hold in most of the sedimentary units discussed in this thesis, so there must be some other minerals producing these concentrations. Of these minerals, probably the heavy minerals play an important role, and probably small amounts of clay minerals may also contribute.

The climate of Bahrain is extremely arid, and evaporation exceeds precipitation, leading to concentration of the interstitial waters and the lowering of the groundwater table which causes water to flow through the sediments. These interstitial waters are complex in origin, and appear to have originated by the mixing of sea water derived from the adjacent Gulf, with groundwater derived from the adjoining bedrock and with surface water. The surface water is introduced either by direct precipitation or runoff or both. The seawater from the Gulf may pass through the sediments either by "seepage reflux" or across the surface as "flood recharge", or both. The continental groundwaters are derived from the fresh water aquifers in the Tertiary rocks, and pass through the sediments from the landward direction. The rainwater may be directly precipitated onto the sabkha, or may be as runoff from the surface of the Tertiary rocks of the backslope, in either case it presumably percolates downwards through the sediments.

Due to the abundance of quartz and the absence of fine grained carbonates and clays reaction between the interstitial waters and the host sediments are minimal. The diagenetic minerals have mainly been produced by precipitation from concentrating interstitial waters. The first mineral to precipitate is aragonite, this is hard to detect in the presence of abundant detrital skeletal carbonates. Further concentration results in the precipitation of gypsum. Discoidal gypsum present in the surface sediments as individual crystals or nodular groups are developed in environments of high salinity and high sulphate content. When crystallisation is fast the poikilotopic type enclosing host sediments is formed, but when crystallisation is slow, the clear displacive type is formed. These discoids sometimes grow together to form nodules. Close to the Tertiary backslope gypsum is present as needles, rods and nodules consisting of needles and rods. This form of gypsum is precipitated when the groundwaters contain a lower concentration of total dissolved solids, in this case due to the mixing with continental groundwater. The concentration of sulphate was still high because the groundwaters are enriched in that ion, partly because

the local rainfall is enriched in it and partly as the result of solution of earlier evaporites. Anhydrite present in the surface sediments as nodules have, atleast in part, a gypsum precursor and are not found close to the Tertiary backslope where the groundwaters are diluted. In the salt pan, gypsum is present as a primary precipitate; freely precipitating subaqueously as needles and rods. Evaporation and concentration of the water in the pan until complete dryness led to the formation of different habits of gypsum, which probably precipitated at different stages of concentration. These are; needles with six crystal faces parallel to the C-crystallographic axis, needles with four crystal faces parallel to the C-crystallographic axis, rods, short selenite-like crystals, crystals which look like discoids but with well-developed crystal faces and discoids. Some of this gypsum was later dehydrated to anhydrite. The salt pan was later covered with terrigenous sediments within which discoidal crystals precipitated. Evaporation of shallow waters in the salt pan leads to precipitation of halite which is ephemeral, and is not preserved because of the high humidity.

Further concentration of the groundwaters has led to the precipitation of celestite. Other diagenetic minerals such as dolomite and magnesite are generally scarce and are produced by reaction between the brine and sediments. Their limited occurrence is due to the general absence of fine grained aragonite and the abundance of quartz and coarse sand grade to gravel grade skeletal fragments.

Diagenesis of the primary carbonate grains is mainly by micritization, and a process of dissolution and reprecipitation. Some of the calcium carbonate released by solution of the aragonite grains has precipitated as an overgrowth on quartz and carbonate grains, where in some cases it acted as a cement.

Highly soluble salts were not deposited due to the high relative humidity in Bahrain.

From the previous summary it is evident that in a quartz-rich sabkha the brine produced by evaporation is depleted in calcium, sulphate and strontium, and is enriched in sodium, magnesium, potassium and chloride.

### Comparison with Other Coastal Sabkhas:

The southwest sabkha of Bahrain has similarity with other areas (e.g. Laguna Madre, Texas, Masson, 1955; the coasts of the United Arab Emirates, Qatar, Kuwait and Saudi Arabia, the Arabian Gulf, Evans et al, 1964 and 1969; Shearman, 1966, 1978; Kinsman, 1964, 1969; Butler, 1965, 1969, 1970; Bush, 1973; Hsu and Schneider, 1973; Schneider, 1974; Illing et al, 1965; Saleh, 1979; Johnson et al, 1978; the Ranns of Kutch, India, Glennie and Evans, 1976; the Gulf of California, Kinsman, 1969; Shearman, 1970; Phleger, 1969; Libya, Sherif, 1978; and Egypt, Gavish, 1974; Levy, 1977a and b; West et al, 1979; Hassouba, 1980) in that they are low accretionary plains subjected to arid to semi-arid conditions, are the site of deposition of evaporites, and the groundwaters have originated from several sources and have become concentrated as a result of evaporation.

The southwest sabkha is similar to some sabkhas (e.g. the sabkhas southeast of Qatar, Shinn, 1973; the east coast of Saudi Arabia, Johnson et al, 1978; the northwest Gulf of California, Kinsman, 1969; the Ranns of Kutch, India, Glennie and Evans, 1976; the Gulf of Suez, Egypt, Gavish, 1974; parts of north Sinai, Egypt, Levy, 1977b) in that they are almost all formed of detrital siliciclastic sediments with a low carbonate content, and the scientific investigations carried out on most of these sabkhas has been at a reconnaissance level.

Umm Said sabkha, southeast of Qatar (Shinn, 1973) is very similar to that of the southwest sabkha of Bahrain, both being coastal sabkhas of a limited areal extent, subjected to arid conditions, where the potential rate of evaporation is considerably higher than the annual precipitation, and are almost all formed of detrital siliciclastic sediments with a low carbonate content. The sedimentary sequence at Umm Said is 30m. thick and consists mainly of medium to fine feldspathic quartzose sand which contains 5 - 15% of sand sized fragments of Eocene dolomite and small amounts of other carbonate minerals. Shinn, 1973, assumes that this sequence ^{was} deposited during two phases of regressive sedimentation separated by a 2 - 3m. thick transgressive carbonate layer. In the southwest sabkha, because the origin of the coastal plain is complex, the sedimentary sequence is more complex. than that of Umm Said; whereby terrigenous desert dunes are overlain in the northwest of the sabkha by sediments of the regressive phase of a marine strait, in the east of the sabkha by lagoonal and salt pan

sediments, and to the south by the sediments of a regressive cycle produced by progradation of the coastline. In addition to these sedimentary sequences, the surface sediments contain diagenetic minerals within them. In both sabkhas, the principal sedimentary processes are relatively simple; the dunes crossed the Gulf of Salwa when sea level was lower and migrated to accumulate along the windward side of Bahrain and the leeward side of Qatar. Then the sea level rose, wind played an important role in deflating the inland areas of the southwest sabkha, while at Umm Said aeolian sand is blown into the sea. In the southwest sabkha, waves, tidal currents and longshore drifts played an important role in reworking this dune sand and mixing it with locally produced carbonates and distributing it to the south to deposit it at the gently inclined accretion plain. At Umm Said waves and tidal currents reworked the dune sands which accumulated on the beach and foreshore and distributed them down the steep subtidal accretion slope where they attained characteristic seaward dipping accretion beddings. Due to the high rates of sedimentation, locally produced carbonates are almost swamped. According to Shinn, 1973, this type of sabkha, will within a few thousand years, when the present sand supply is exhausted, revert to carbonate coastal sedimentation similar to those of the other areas in the Arabian Gulf, and will be preserved as a porous, siliciclastic sand lens surrounded by carbonates.

The coastal sabkhas of the Ranns of Kutch, India, Glennie and Evans, 1976; parts of northeast Egypt, Levy, 1977b; and the northwest Gulf of California, Kinsman, 1969, are similar to the southwest sabkha of Bahrain in being subjected to arid to semi-arid conditions, where the potential rate of evaporation is higher than the annual precipitation, and are almost formed of detrital siliciclastic sediments with a low carbonate content. One of the major differences between these sabkhas and the southwest sabkha of Bahrain is the source of the siliciclastic sediments. The sediments of the southwest sabkha, Bahrain, have an aeolian origin, while those of the other areas generally have a fluvial origin. This is reflected in the grain types and mineralogy. With the fluvial sediments there is a lack of locally produced carbonates due to the environment and to the high rate of clastic sediment input and silt and clay grade material are present with abundant clay minerals. In the southwest sabkha locally produced carbonates are mixed with the aeolian quartz sand and silt

and clay grade materials are generally low, and even when material of this grade is present the proportion of clay minerals is small. Another difference is the presence of some algal mats and halite in these other areas, while in the southwest sabkha, algal mats are poorly developed as the conditions are not favourable for their growth. In all the areas, gypsum is the main diagenetic mineral present, anhydrite occurs in the southwest sabkha and the sabkhas northwest of the Gulf of California. Dolomitization is generally limited. The supratidal areas in all these sabkhas have developed through the normal processes of subtidal, intertidal and supratidal sedimentation, but in the southwest sabkha a relatively greater proportion of its area has been produced by deflation rather than accretion.

In the previous discussion quartz-rich sabkhas were compared with the southwest sabkha. In the following discussion, the southwest sabkha will be compared with carbonate sabkhas (e.g. Libya, Sherif, 1978; west of Alexandria, Egypt, West et al, 1979; Hassouba, 1980; the United Arab Emirates and Qatar, Evans et al, 1969; Shearman, 1966, 1978; Kinsman, 1964, 1966, 1969; Butler, 1969, 1970; Bush, 1973; Illing et al, 1965; Shinn, 1973) with particular emphasis on those of the southeast coast of the United Arab Emirates. The main similarities between them are; they are coastal sabkhas, subjected to arid to semi-arid conditions, where the potential rate of evaporation is considerably higher than the annual precipitation and diagenetic minerals are common. Some of the differences between the southwest sabkha and the carbonate dominated part of these carbonate sabkhas is that it is less extensive than these other coastal sabkhas, a greater proportion of its area is produced by deflation rather than by accretion, and its sediments are composed of reworked aeolian sands, while the carbonate sabkhas are mainly formed of locally produced carbonates. However, it must be remembered that behind the accretional carbonate sabkha of the United Arab Emirates, there are extensive areas of sabkha produced by deflation of dunes composed of sand grade quartz and low magnesium calcite.

The following is a comparison between the southwest sabkha and the sabkha southeast of the United Arab Emirates (of Abu Dhabi). At Abu Dhabi the sedimentary sequence consists of quartzose carbonate sand overlain by muddy carbonate sand overlain by a unit which contains

a number of different sediment types consisting of old and recent algal mats, carbonate mud and sand, carbonate sand and diagenetic sulphate and carbonate minerals. The quartzose carbonate sand represents the remnant dune system described above, it is overlain by a shallowing upward regressive sequence consisting of a subtidal marine facies, the muddy carbonate sand, of lagoonal aragonite muds and pelleted aragonite muds, overlain by an intertidal facies, the algal mats, overlain by supratidal flats, the carbonate sands and mud with diagenetic minerals. The primary supratidal flat sediments are mainly wind-blown admixtures of locally produced carbonates and some lagoonal aragonite muds washed over the sabkha during storms. A striking feature of this sabkha is its uniformity throughout most of the coast, apart from the exposed coasts where algal mats^{are} absent and the intertidal zone presents a steep beach face capped by beach ridges (Evans et al., 1964). The sedimentary sequence of the southwest sabkha was discussed in the comparison with the Umm Said sabkha. It is more complex and varied than the Abu Dhabi sabkha, but in principal they are both comprised of a pre-transgressive dune system overlain by a regressive cycle, in the case of Abu Dhabi the sediments are carbonates and carbonate muds with intertidal algal mats, while in the case of the southwest sabkha the sediments are siliclastics mixed with carbonates, algal mats are generally absent or poorly developed. It is this difference in sediment types which underlies the difference in diagenetic minerals present; gypsum and anhydrite are common in the southwest sabkha but dolomitization is limited and magnesite and halite are rarely present within the sediments, while in the sabkhas at Abu Dhabi, gypsum, anhydrite and dolomite are common, halite is present in very small amounts in the surface sediments and magnesite is locally important.

The differences between the host sediments of the southwest sabkha and those of other areas results in there being differences in the composition of the interstitial brines. In the southwest sabkha the final brines are depleted in calcium, strontium and sulphate, and enriched in chloride, sodium, magnesium and potassium. The sabkhas of the United Arab Emirates, Qatar, Egypt and Libya have final brines enriched in calcium and chloride and depleted in magnesium and sulphate due to dolomitization (Kinsman, 1964; Shearman, 1966; Bush, 1973; Levy, 1977; Sherif, 1978).

**Conclusion:**

The southwest sabkha provides an understanding of the processes and products of sedimentation of coastal sabkhas produced in quartz-rich sediments, and it demonstrates that in this type of environment numerous facies may exist in very close proximity, so that in the geologic record rapid local lithological variations may be expected both vertically and laterally.

## REFERENCES

## References:

- Al-Sayari, S. S. and Zotl, J. G. (eds.), 1978, Quaternary Period in Saudi Arabia. Springer-Verlag, Wien - New York.
- Adams, J. E. and Rhodes, M. L., 1960, Dolomitisation by seepage refluxion. *Bul. Am. Assoc. Petrol. Geologists.*, v, 44, pp. 1912-1920.
- Bahrain Surface Materials Resources Survey, 1976, Geomorphological geological and pedological survey of the surface materials of Bahrain. Unpublished report to the Government of Bahrain (6 vols.).
- Bathurst, R. G. C., 1971, Carbonate sediments and their diagenesis. *Developments in Sedimentology* 12. Elsevier, 620pp.
- Bigarella, J. J., 1972, Eolian environments - their characteristics, recognition and importance. In: *Recognition of ancient sedimentary environments*, eds. J. K. Rigby and W. K. Hamblin. S.E.P.M. special publication No. 16, pp. 12-62.
- Bonython, W. C., 1966, Factors determining the rate of solar evaporation in the production of salt. 2nd. Symposium on Salt. N. Ohio Geological Society, pp. 152-167.
- Borchert, H. and Muir, R. O., 1964, Salt deposits, the origin, metamorphism and deformation of evaporites. D. Van Nostrand Co. Ltd.
- Brunsdon, D., Doornkamp, J. C. and Jones, D. K. C. (eds.), 1980, Geology, geomorphology and pedology of Bahrain. GeoAbstracts Ltd. Norwich.
- Bush, P. R., 1970, A rapid method for the determination of carbonate carbon and organic carbon. *Chem. Geol.*, 6, pp. 59-62.
- Bush, P. R., 1973, Some aspects of the diagenetic history of the sabkha in Abu Dhabi, Persian Gulf. In: *The Persian Gulf*, ed B. H. Purser. Springer - Verlag. Berlin. pp. 395-408.
- Bush, P. R., 1973, Sedimentology and ground water chemistry of some Recent coastal plain sediments, Abu Dhabi, Trucial Coast, Persian Gulf. Ph.D. thesis, University of London.
- Butler, G. P., 1965, Early diagenesis in the Recent sediments of the Trucial Coast of the Persian Gulf. Unpublished M.Sc. thesis, University of London, 251 p.
- Butler, G. P., 1969, Modern evaporite deposition and geochemistry of coexisting brines, the sabkhas, Trucial Coast, Arabian Gulf. *J.Sedim.Petrol.*, v.39, pp. 79-80.

- Butler, G. P., 1970, Holocene gypsum and anhydrite of the Abu Dhabi sabkha, Trucial Coast. 3rd. Symposium on Salt, Cleveland, Ohio, N. Ohio Geological Society.
- Butler, G. P., 1971, Origin and controls on distribution of arid supratidal (sabkha) dolomite, Abu Dhabi, Trucial Coast. Am.Assoc.Petroleum Geol., v.55, No. 2, pp. 332-333.
- Butler, G. P., 1973, Strontium geochemistry of modern and ancient calcium sulphate minerals, In: The Persian Gulf, ed. B. H. Purser. Springer-Verlag. Berlin. pp. 438-462.
- Butler, G. P., Krouse, R. H. and Mitchell, R., 1973, Sulphur-isotope geochemistry of an arid supratidal evaporite environment, Trucial Coast. In: The Persian Gulf, ed. B. H. Purser. Springer-Verlag. Berlin. pp. 423-453.
- Cavallier, G., 1975, Le tertiaire du Qatar en affleurement. Lexique stratigraphique International, 3, 10, 63, pp. 39-120.
- Clarke, F. W., 1924, Data of geochemistry. Bull.U.S.G.S., pp. 770-716.
- Cuff, G., 1972, The crystallography and geochemistry of authigenic calcium sulphate and carbonate minerals of the Recent sediments of the Trucial Coast. Ph.D. thesis, University of London.
- Curray, J. R., 1961, Late Quaternary sea level, A discussion. Bull. Geol.Soc.Am., 72, pp. 1707-1712.
- Curtis, R., Evans, G., Kinsman, D. J. J. and Shearman D. J., 1963, Association of dolomite and anhydrite in Recent sediments of the Persian Gulf. Nature, v.197, No. 4868, pp.679-680.
- Deffeyes, K. S., Lucia, F. J. and Weyl, D. K., 1965, Dolomitization of Recent and Plio-Pleistocene sediments by marine evaporite waters on Bonaire, Netherlands Antilles. In: Dolomitization and limestone diagenesis, eds. L. C. Pray and R.C.Murray. S.E.P.M. special publication No. 13, pp. 71-88.
- Emery, K. O., 1956, Sediments and water of the Persian Gulf. Am.Assoc Petrol.Geol.Bull., v.40, pp. 2354-2383.
- Evamy, B. D., 1973, The precipitation of aragonite and its alteration to calcite on the Trucial Coast of the Persian Gulf. In: The Persian Gulf, ed. B. H. Purser. Springer-Verlag. Berlin. pp. 329-342.
- Evans, G., 1966, The Recent sedimentary facies of the Persian Gulf region. Phil.Trans.Roy.Soc.London, Ser.A, v.259, No.1099, pp. 291-298.
- Evans, G., 1979, Quaternary transgressions and regressions. J.Geol.

- Soc.Lond., v.136, part 2, pp. 125-132.
- Evans, G. and Bush, P. R., 1969, Some sedimentological and oceanographic observations on a Persian Gulf lagoon. In: Coastal lagoons, ed. A. A. Castanares and F. B. Phleger. Mem. Simp.Intern.Lagunas Costeras, UNAM-UNESCO, Mexico, pp. 155-170.
- Evans, G., Kinsman, D. J. J. and Shearman, D. J., 1964, A reconnaissance survey of the environments of Recent carbonate sedimentation along the Trucial Coast, Persian Gulf. In: Deltaic and shallow marine deposits, ed. L. M. J. U. Van Straaten Elsevier, Amsterdam. pp. 129-135.
- Evans, G., Schmidt, V., Bush, P. R. and Nelson, H., 1969, Stratigraphy and geologic history of the sabkha, Abu Dhabi, Persian Gulf. *Sedimentology*, v.12, pp. 145-159.
- Evans, G and Shearman, D. J., 1964, Recent celestite from the sediments of the Trucial Coast of the Persian Gulf. *Nature*, 202;No. 4930, pp. 385-386.
- Fairbridge, R. W., 1961, Eustatic changes in sea level. Physics and chemistry of the earth, London, Pergamon Press, v.4, pp. 99-185.
- Friedman, G. M. and Sanders, J. E., 1967, Origin and occurrence of dolostones. In: Carbonate rocks, part A, ed. G. V. Chilingar et al. Elsevier Pub. Co. New York. pp. 267-348.
- Gavish, E., 1974, Geochemistry and mineralogy of a recent sabkha along the coast of Sinai, Gulf of Suez. *Sedimentology*, v.21, pp. 397-414.
- Glennie, K. W., 1970, Desert sedimentary environments. Developments in *Sedimentology*, v.14, 222. Elsevier, Amsterdam.
- Glennie, K. W. and Evans, G., 1976, A reconnaissance of the Recent sediments of the Rams of Kutch, India. *Sedimentology*, v.23, pp. 623-647.
- Groot, de, K., 1973, Geochemistry of tidal flat brines at Umm Said, SE Qatar, Persian Gulf. In: The Persian Gulf, ed. B. H. Purser. Springer-Verlag. Berlin. pp.377-394.
- Gunter, G. M., 1957, In: Treatise on marine ecology and Palaeoecology, ed. J. W. Hedgepath. Geol.Soc.Amer.Mem. v.67, pp. 159-184.
- Hardie, L. A., 1967, Gypsum-anhydrite equilibrium at one atmosphere pressure. Abstract, G.S.A. meeting, Miami. The Am. Miner., v.52, pp.171-200.

- Hassouba, A. B. H., 1980, Quaternary sediments from the coastal plain of north western Egypt (from Alexandria to El Omayed) Ph.D. thesis, University of London.
- Hassouba, H. and Shaw, H. F., 1980, The occurrence of palygorskite in quaternary sediments of the coastal plain of north west Egypt. *Clay Minerals*, v.15, pp. 77-83.
- Houbolt, J. J. H. C., 1957, Surface sediments of the Persian Gulf near the Qatar Peninsula. Ph.D. thesis, University of Utrecht. Den Haag. Mouton & Co.
- Hsu, K. J. and Schneider, J. F., 1973, Progress report on dolomitization-hydrology of Abu Dhabi sabkhas, Arabian Gulf. In: *The Persian Gulf*, ed. B. H. Purser. Springer-Verlag. Berlin. pp.409-422.
- Hunt, C. B. and Washburn, A. L., 1966, Patterned grounds. U.S.G.S. Prof. Paper, 494B, B104-B133.
- Illing L. V., Wells, A. J. and Taylor, J. C. M., 1965, Penecontemporary dolomite in the Persian Gulf, S.E.P.M. special publication, 13, pp. 89-111.
- * Johnson, D. H., Kamal, M. R., Pierson, G. O. and Ramsay, J. B., 1978, Sabkhas of eastern Saudi Arabia. In: *Quaternary period in Saudi Arabia*, ed. S. S. Al-Sayari and J. G. Zotl. Springer-Verlag. Wien-New York. pp.84-93.
- Kassler, P., 1973, The structural and geomorphic evolution of the Persian Gulf. In: *The Persian Gulf*, ed. B. H. Purser. Springer-Verlag. Berlin. pp.11-32.
- Kastner, M., 1970, An inclusion hourglass pattern in synthetic gypsum *Am.Miner.*, v.55, pp.212-213.
- Kendall, A. C., 1978, Facies models 11: Continental and supratidal (sabkha) evaporites. *Geosci.Canada.*, v.3, No.2, pp.66-78.
- Kendall, C. G. St. C. and Skipwith, P. A. d'E., 1968, Recent algal mats of a Persian Gulf lagoon. *J.Sedim,Petrol.*, v.38, pp. 1040-1058.
- Kendall, C. G. St.C. and Skipwith, P. A. d'E, 1969a, Holocene shallow water carbonate and evaporite sediments of Khor al Bazam, Abu Dhabi, Southwest Persian Gulf. *Bull.Am. Assoc.Petrol.Geol.*, v.53, pp. 841-849.

* Italconsult, 1971, Water and agricultural studies in Bahrain. Unpublished report to the government of Saudi Arabia.

- Kendall, C. G. St.C. and Skipwith, P. A. d'E., 1969b, Geomorphology of a recent shallow water carbonate province: Khor al Bazam, Trucial Coast, Southwest Persian Gulf. Bull.Geol.Soc.Am., v.80, pp. 865-891.
- Kinsman, D. J. J., 1964, Recent carbonate sedimentation near Abu Dhabi Trucial Coast, Persian Gulf. Unpublished Ph.D. thesis, University of London.
- Kinsman, D. J. J., 1964, The Recent carbonate sediments near Halat el Bahrani, Trucial Coast, Persian Gulf. In: Deltaic and shallow marine deposits, ed. L. M. J. U. Van Straaten. Elsevier. Amsterdam. pp. 185-192.
- Kinsman, D. J. J., 1966, Gypsum and anhydrite of Recent age, Trucial Coast, Persian Gulf. In: 2nd. Symposium on Salt, ed. J. L. Rau. Cleveland, Ohio, N. Ohio Geological Society. pp. 302-326.
- Kinsman, D. J. J., 1969, Modes of formation, sedimentary associations, and diagenetic features of shallow water and supratidal evaporites. Am.Assoc.Petrol.Geol.Bull., v.53, No. 4, pp. 830-840.
- Kinsman, D. J. J., 1971, Early diagenesis of carbonate sediments in a supratidal evaporitic setting. Am.Assoc.Petrol. Geol. Bull., v.55, part I, pp. 167-168.
- Kinsman, D. J. J., 1976, Evaporites: relative humidity control of primary mineral facies. J.Sedim.Petrol., v.46, No.2, pp.273-279
- Kinsman, D. J. J. and Holland, H. D., 1969, The coprecipitation of cations with  $\text{CaCO}_3$ -IV. The coprecipitation of  $\text{Sr}^{2+}$  with aragonite between  $16^\circ$  and  $96^\circ\text{C}$ . Geochim.Cosmochim.Acta. v.33, pp. 1-17.
- Lees, G. M., 1948, The physical geography of South-East Arabia. Geogr. Journ., v.121, p. 141.
- Lees, G. M. and Falcon, N. L., 1952, The geographical history of the Mesopotamian plains. Geogr.Journ., v.116, pp. 24-39.
- Levy, Y., 1977a, The origin and evolution of brine in coastal sabkhas, northern Sinai. J.Sedim.Petrol., v.47, No, 1, pp. 451-462.
- Levy, Y., 1977b, Description and mode of formation of the supratidal evaporite facies in Northern Sinai coastal plain. J, Sedim.Petrol., v.25, pp. 463-474.
- Masson, P. H., 1955, An occurrence of gypsum in Southwest Texas. J, Sedim.Petrol., v.25, pp. 72-77.

- McKenzie, J. A. and Hsu, K. J., 1974, Isotope hydrology of the coastal sabkha of Abu Dhabi, Site of Recent dolomitization. Geol.Soc.Am.Abstr., v.6, No.7, pp. 864-865.
- Messrs. Sandbergs, 1975, (in association with Engineering Geology Ltd.) A review of material aspects of geological and resources studies of Bahrain: 1908-1974. Unpublished report to the Government of Bahrain (2 vols.)
- Murray, R. C., 1969, Hydrology of South Bonaire, N. A. A rock selective dolomitization model. J.Sedim.Petrol., v.39, pp. 1007-1013.
- Park, R. K., 1973, Algal belt sedimentation of the Trucial Coast, Arabian Gulf. Ph.D. thesis, University of Reading.
- Patterson, R. J. and Kinsman, D. J. J., 1977, Marine and continental groundwater sources in a Persian Gulf coastal sabkha. In: Studies in Geology. Am.Assoc.Petrol.Geol., v.4. Tulsa. pp. 381-397.
- Persian Gulf Pilot, 1955, The Persian Gulf and its approaches, from Ras al Hadd in the southwest to Cape Monze in the east. Hydrology Dept., British Navy, 10th.ed., pp. 312.
- Phleger, F. B., 1969, A modern evaporite deposit in Mexico. Bull.Am. Assoc.Petrol.Geol., v.53, pp. 824-829.
- Pilgrim, G. E., 1908, The geology of the Persian Gulf and the adjoining portions of Persia and Arabia. Mem.Geol.Surv.India. v. XXXIV (4).
- Powers, R. W., Ramirez, L. F., Redmond, C. D. and Elberg, E. L. Jr., 1966, Geology of the Arabian peninsula - sedimentary geology of Saudi Arabia. U.S.G.S. Prof. Paper 560D.
- Privett, D. W., 1959, Monthly charts of evaporation from the northern Indian Ocean (including the Red Sea and the Persian Gulf). Q.J.R.Met.Soc. v.85, pp. 424-478.
- Purdy, E. G., 1963, Recent calcium carbonate facies of the Great Bahama Bank. Journ.Geol. v.71, pp. 334-355, 472-497.
- Purser, B. H. (ed.), 1973, The Persian Gulf, Holocene carbonate sedimentation and diagenesis in a shallow epicontinental sea. Springer-Verlag, Berlin.
- Purser, B. H. and Seibold, E., 1973, The principal environmental factors influencing Holocene sedimentation and diagenesis in the Persian Gulf. In: The Persian Gulf, ed. B. H. Purser. Springer-Verlag. Berlin. pp. 1-10.
- Q.Jl.Engng.Geol., 1972, Description of soils and rocks. In: The preparation of maps and plans in terms of engineering geology. A report by the Geological Society Group Working Party.

- Q.Jl.Engng.Geol., v.5, No.4, Chap.5, pp. 313-324.
- Saleh, A. A., 1979, Recent algal mats and Quaternary carbonate sediments of al-Khiran, Kuwait. Ph.D. thesis, University of London.
- Schneider, J. F., 1974, Physical hydrology of the coastal sabkha of Abu Dhabi, site of recent dolomitization. Geol.Soc. Am.Abstr., v.6, No.7, p. 942.
- Schreiber, B. C., 1978, Environments of subaqueous gypsum deposition. In: Marine Evaporites, ed. W. E. Dean and B. C. Schreiber, S.E.P.M. short course No.4, Oklahoma City, pp. 43-74.
- Seibold, E. and Vollbrecht, K., 1969, Die Bodengestalt des Perischen Golfs. "METEO" Forsch.Ergebnisse, Reihe C, No.2, pp. 29-56.
- Shearman, D. J., 1963, Recent anhydrite, gypsum, dolomite, and halite from the coastal states of the Arabian shore of the Persian Gulf. Geol.Soc.London, Proc. No. 607, pp 63-65.
- Shearman, D. J., 1966, Origin of marine evaporites by diagenesis. Inst. Mining Met.Trans., v. B75, pp 207-215.
- * Shearman, D. J., 1978, Evaporites of coastal sabkhas. In: Marine Evaporites, eds. W. Dean and B. C. Schreiber. S.E.P.M. short course No.4, Oklahoma City, pp. 6-42.
- Shearman, D. J., 1979, A field test for the identification of gypsum in soils and sediments. Q.Jl.Engng.Geol., v.12, p. 51.
- Shinn, E. A., 1973, Carbonate coastal accretion in an area of longshore transport, NE Qatar, Persian Gulf. Ed. B. H. Purser. Springer-Verlag. Berlin. pp.179-192.
- Shinn, E. A., 1973, Sedimentary accretion along the leeward SE coast of Qatar Peninsula, Persian Gulf. In: The Persian Gulf, ed. B. H. Purser. Springer-Verlag. Berlin. pp, 199-210.
- Shinn, E. A., Ginsburg, R. N. and Lloyd, R. M., 1965, Recent supratidal dolomite from Andros Island, Bahamas. In: Dolomitization and limestone diagenesis, eds. L. C. Pray and R. C. Murray. S.E.P.M. Special Publication, No, 13, pp. 112-123.
- Stoffers, P., and Ross, D. A., 1979, Late Pleistocene and Holocene sedimentation in the Persian Gulf - Gulf of Oman. Sedim.Geol., v.23, No.1/4, pp, 181-208.
- Sugden, W, 1963, The hydrology of the Persian Gulf and its significance in respect to evaporite deposition. Am.Jour.Science, v. 261, pp. 741-755.
- * Shearman, D.J., 1970, Recent halite rock, Baja California, Mexico. Trans. AIME, 79, pp. 155-162.

- Taylor, J. C. M. and Illing, L. V., 1969, Holocene intertidal calcium carbonate cementation, Qatar, Persian Gulf. *Sedimentology*, v.12, pp. 69-107.
- Thode, H. G., Monster, J. and Dunford, H. B., 1961, Sulphur-isotope geochemistry. *Geochim.Cosmochim.Acta.*, v.25, pp. 159-174.
- West, I. M., Ali, Y. A. and Hilmy, M. E., 1979, Primary gypsum nodules in a modern sabkha on the Mediterranean coast of Egypt. *Geology*, v.7, pp. 354-358.
- Willis, R. P., 1967, Geology of the Arabian Peninsula - Bahrain. U.S.G.S., Prof. Paper 560E.
- Wright, E. P., 1967, Report on the groundwater resources of Bahrain Island, Arabian Gulf. Unpublished report, Government of Bahrain.
- Wright, E. P. and Ayub, M., 1975, Groundwater abstraction and irrigation in Bahrain (Interim Report) Dept. of Agriculture, Bahrain.

## APPENDIX I

### Mineralogical Composition of the Sediments

Pit	Sample	Calcite	IMC	Aragonite	Dolomite	Magne- site	Gypsum	Anhydrite	Cele- stite	Quartz	Felspar	Arax/Cal	Carbonates
11/22	6/1073	7.31	2.43	34.86	1.43	0.0	0.0	0.0	0.0	52.48	1.5	4.77	46.03
	1072	14.51	0.0	0.0	3.58	0.0	0.0	0.0	0.0	71.0	10.91	0.0	18.09
11/23	1076	5.76	0.0	0.0	2.98	0.0	14.58	0.0	0.0	73.86	2.81	0.0	8.74
	1075	13.76	1.07	0.0	1.92	0.0	0.0	0.0	0.0	78.79	4.45	0.0	16.75
11/25	1079	10.58	1.61	0.0	4.04	0.0	6.58	0.0	3.82	65.87	7.51	0.0	16.23
	1078	5.32	1.75	0.0	1.66	0.0	0.0	0.0	0.0	88.35	2.93	0.0	8.73
11/26	1082	8.02	1.81	7.75	2.53	0.0	13.11	0.0	1.32	54.59	5.87	.99	20.11
	1081	13.19	2.6	0.0	1.84	0.0	2.5	0.0	0.0	72.25	7.62	0.0	17.63
11/27	1085	7.86	0.0	23.91	3.51	0.0	43.31	0.0	0.0	20.51	0.9	3.04	35.28
	1084	5.64	0.0	77.54	2.16	0.0	0.0	0.0	0.0	13.81	0.85	13.75	85.34
11/28	1093	4.32	6.91	66.36	3.12	0.0	1.94	0.0	0.0	15.43	1.92	15.36	80.71
	1092	5.21	8.82	55.92	4.8	0.0	0.0	0.0	0.0	23.9	1.34	10.73	74.75
	1091	5.5	7.89	46.58	2.43	0.0	6.78	0.0	0.0	27.48	3.35	8.47	62.40
	1090	8.94	0.84	21.48	1.25	0.0	0.0	0.0	0.0	65.06	2.43	2.4	32.51
	1089	13.33	1.68	0.0	9.85	0.0	0.0	0.0	0.0	67.59	7.55	0.0	24.86
	1088	5.21	2.35	25.96	2.52	0.0	0.0	0.0	0.0	59.15	4.8	4.98	36.04
13/1	1097	5.47	0.0	86.08	3.78	0.0	0.0	0.0	0.0	3.91	0.75	15.74	95.33
	1096	6.52	10.07	65.54	2.8	0.0	0.0	0.0	0.0	9.21	5.86	10.05	34.93
	1094	12.99	2.17	33.44	1.67	0.0	0.0	0.0	0.0	45.09	4.64	2.57	50.27
13/2	1101	5.89	3.18	40.2	0.0	0.0	0.0	0.0	3.69	44.87	2.18	6.83	49.27
	1100	5.46	2.29	45.61	0.0	0.0	0.0	0.0	0.0	43.55	3.09	8.35	53.36
	1099	10.54	1.38	0.0	2.24	0.0	0.0	0.0	0.0	81.56	4.26	0.0	14.16
13/3	1106	5.27	0.0	0.0	0.0	0.0	58.3	0.0	3.62	28.76	4.05	0.0	5.27
	1105	8.73	1.02	0.0	2.49	0.0	0.0	0.0	1.9	81.31	4.56	0.0	12.24
	1104	15.91	0.0	0.0	2.5	0.0	0.0	0.0	12.21	62.28	4.1	0.0	18.41
	1103	12.43	1.88	0.0	2.17	0.0	0.0	0.0	0.0	78.9	4.61	0.0	16.48
13/16	1141	14.65	1.18	0.0	4.06	0.0	1.39	0.0	0.0	72.07	6.66	0.0	19.89
13/17	1138	11.47	0.86	6.43	1.94	0.0	4.39	0.0	0.0	72.37	2.55	.56	20.64
13/18	1136	13.46	2.0	7.48	2.31	0.0	1.06	0.0	0.0	72.12	1.57	.56	23.25
13/27	1120	7.17	0.0	0.0	0.64	0.0	0.0	0.0	0.0	91.26	0.93	0.0	7.81
	1119	11.65	1.12	0.0	2.28	0.0	0.0	0.0	0.0	78.28	6.67	0.0	15.05
13/28	1116	10.28	0.0	0.0	3.54	0.0	0.0	0.0	0.0	83.68	2.5	0.0	13.82
13/29	1128	10.06	1.02	0.0	2.16	0.0	2.92	0.0	0.0	82.19	1.65	0.0	13.24
13/33	1148	5.5	0.0	60.06	1.11	0.0	0.0	0.0	0.0	30.3	2.53	10.92	66.67
	1149	6.53	0.0	24.84	0.73	0.0	1.02	0.0	0.0	61.04	5.84	3.8	32.1
13/34	1151	6.58	0.0	33.22	2.7	0.0	0.0	0.0	0.0	56.34	1.06	5.06	42.6
	1150	9.18	0.0	19.44	0.54	0.0	1.37	0.0	0.0	65.88	3.58	2.12	29.16
13/35	1154	4.73	0.0	18.96	1.73	0.0	0.0	0.0	0.0	71.23	2.85	4.01	25.42
	1153	8.48	0.0	9.89	0.57	0.0	0.6	0.0	0.0	78.53	1.92	1.17	18.94
13/36	1157	9.48	0.0	10.01	1.73	0.0	0.0	0.0	0.0	77.24	1.55	1.06	21.22
	1156	14.63	0.0	9.55	1.91	0.0	0.0	0.0	0.0	68.84	5.08	.65	26.09
	1155	16.01	0.0	0.0	2.94	0.0	0.0	0.0	0.0	74.41	6.64	0.0	18.95
13/37	1110	10.46	0.0	0.0	3.37	0.0	4.39	0.0	0.0	80.28	1.5	0.0	13.83
13/38	1125	11.15	1.52	0.0	1.0	0.0	15.61	0.0	0.0	66.16	4.56	0.0	13.67
	1124	6.3	3.93	0.0	1.36	0.0	43.44	0.0	0.0	43.59	1.38	0.0	11.59
	1123	8.88	0.82	0.0	1.55	0.0	1.55	0.0	0.0	83.46	3.42	0.0	11.57
13/39	362	3.85	0.0	0.0	1.47	0.0	0.0	0.0	0.0	92.56	2.12	0.0	5.32
	364	6.71	0.0	0.0	1.99	0.0	0.0	0.0	0.0	89.01	2.29	0.0	8.7
13/40	359	6.97	0.0	0.0	1.66	0.0	0.0	0.0	0.0	87.23	4.14	0.0	8.63
13/41	358	4.87	0.0	0.0	1.95	0.0	0.0	0.0	0.0	90.8	2.37	0.0	6.82
13/42	1131	14.75	2.14	0.0	2.55	0.0	0.0	0.0	0.0	72.67	7.89	0.0	19.44
	1130	15.15	0.0	0.0	2.26	0.0	0.0	0.0	0.0	77.13	5.46	0.0	17.41
13/43	355	8.47	0.0	0.0	1.45	0.0	0.0	0.0	0.0	86.28	3.8	0.0	9.92
13/44	369	16.76	0.0	0.0	2.34	0.0	11.58	2.32	0.0	57.16	8.84	0.0	19.1
	370	10.7	1.97	0.0	2.47	0.0	27.29	0.0	0.0	54.79	2.79	0.0	15.4
13/45	373	12.67	0.0	0.0	3.34	0.0	20.64	0.0	0.0	58.57	4.78	0.0	16.01
	374	0.4	0.0	0.0	0.0	0.0	97.32	1.28	0.0	0.99	0.0	0.0	.4
	375	1.13	0.0	0.0	0.0	0.0	6.96	91.90	0.0	0.0	0.0	0.0	1.13
13/46	381	8.77	4.78	18.17	4.58	0.0	24.76	0.0	0.0	36.87	0.0	.52	36.3
	380	4.05	0.0	0.0	0.0	0.0	78.02	1.89	0.0	16.04	0.0	0.0	4.05
	378	3.7	0.0	0.0	0.0	0.0	91.47	2.79	0.0	2.04	0.0	0.0	3.7
	379	3.16	0.0	0.0	0.0	0.0	0.0	83.85	0.0	12.98	0.0	0.0	3.16
13/47	812	9.59	0.96	48.56	3.08	0.0	18.73	0.0	0.0	16.16	2.47	5.06	62.19
	813	6.49	0.0	34.53	1.22	0.0	34.72	0.0	0.0	21.61	1.42	5.32	42.24
	814	1.5	0.0	0.0	0.0	0.0	98.5	0.0	0.0	0.0	0.0	0.0	1.5
13/49	384	2.21	0.0	0.0	0.0	0.0	90.86	0.0	0.0	6.93	0.0	0.0	2.23
13/50	696	4.65	0.0	0.0	0.0	0.0	43.37	50.0	0.0	1.97	0.0	0.0	4.65
13/52	385	0.92	0.0	0.0	0.0	0.0	0.0	99.08	0.0	0.0	0.0	0.0	.92
13/53	386	6.63	0.83	18.26	2.28	0.0	20.62	0.0	0.0	51.38	0.0	2.75	28.0
13/58	1113	9.99	0.0	0.0	2.27	0.0	0.0	0.0	0.0	81.50	6.24	0.0	12.26
13/59	353	5.58	0.0	0.0	2.85	0.0	0.0	0.0	0.0	88.14	3.42	0.0	8.43
13/60	350	9.83	0.0	0.0	5.0	0.0	0.0	0.0	0.0	79.28	5.89	0.0	14.83
	352	5.99	0.0	0.0	5.11	0.0	0.0	0.0	0.0	85.35	3.55	0.0	11.1
13/61	281	5.67	0.0	0.0	1.8	0.0	0.0	0.0	0.0	89.41	3.12	0.0	7.47
	282	5.43	0.0	0.0	2.81	0.0	0.0	0.0	0.0	88.26	3.49	0.0	8.24
13/62	286	10.98	0.0	0.0	2.79	0.0	0.0	0.0	0.0	80.7	5.54	0.0	13.77
	285	6.16	0.0	0.0	2.26	0.0	0.0	0.0	0.0	88.19	3.39	0.0	8.42
13/63	288	3.23	0.0	0.0	1.85	0.0	0.0	0.0	0.0	92.56	2.46	0.0	5.08
13/64	691	8.66	1.76	10.71	2.27	0.0	30.0	0.0	0.0	43.52	2.09	1.24	23.4
	692	7.17	0.0	0.0	2.32	0.0	44.6	3.59	0.0	36.31	0.0	0.0	9.49
	693	5.21	0.0	0.0	2.06	0.0	89.7	3.03	0.0	0.0	0.0	0.0	7.27
	694	4.17	0.0	0.0	0.0	0.0	30.69	59.0	0.0	6.13	0.0	0.0	4.17
13/70	291	12.63	0.0	14.79	3.29	0.0	2.62	1.48	0.0	61.79	3.41	1.17	30.71
	292	6.59	0.0	47.96	1.61	0.0	9.75	0.0	0.0	30.85	3.24	7.28	56.16
	293	11.2	0.0	0.0	1.8	0.0	0.0	0.0	0.0	85.07	1.93	0.0	13.0
	294	3.35	0.0	0.0	1.73	0.0	0.0	0.95	0.0	91.42	2.55	0.0	5.08
13/72	297	6.94	0.0	0.0	2.42	0.0	0.0	0.0	0.0	87.74	2.9	0.0	9.36
	298	9.13	0.0	0.0	3.11	0.0	4.77	21.23	0.0	60.91	1.96	0.0	11.24
	299	5.11	0.0	0.0	0.0	0.0	10.0	14.66	0.0	65.01	5.22	0.0	5.11
13/74	450	10.12	0.0	0.0	2.3	0.0	1.7	0.0	0.0	82.61	3.27	0.0	12.42
	451	6.83	0.0	0.0	3.21	0.0	1.47	0.0	0.0	85.68	2.81	0.0	10.04
	452	3.58	0.0	0.0	1.54	0.0	3.81	49.7	0.0	40.51	0.87	0.0	5.12
	453	7.05	0.0	0.0	0.0	0.0	84.25	4.64	0.0	4.06	0.0	0.0	7.05

Pit	Sample	Calcite	IMC	Aragonite	Dolomite	Magnetite	Gypsum	Anhydrite	Celestite	Quartz	Felspar	Arag/Cal	Carbonates
13/75	455	11.82	0.0	0.0	3.63	0.0	3.01	0.0	0.0	74.95	6.59	0.0	15.45
	456	5.15	0.0	0.0	2.15	0.0	0.0	0.0	0.0	90.37	2.33	0.0	7.30
	457	.11	0.0	0.0	0.0	0.0	4.47	84.77	0.0	10.64	0.0	0.0	.11
	458	.12	0.0	0.0	0.0	0.0	95.88	0.0	0.0	4.0	0.0	0.0	.12
13/76	459	9.54	0.0	0.0	2.62	0.0	2.03	0.0	0.0	81.27	4.53	0.0	12.16
	460	8.24	0.0	0.0	2.6	0.0	3.96	0.0	0.0	82.72	2.44	0.0	10.84
	461	.13	0.0	0.0	0.0	0.0	70.63	16.01	0.0	13.23	0.0	0.0	.13
13/77	463	6.54	0.0	0.0	1.97	0.0	0.0	0.0	0.0	89.34	2.15	0.0	8.51
	464	.1	0.0	0.0	0.0	0.0	99.11	0.0	0.0	.79	0.0	0.0	.1
	465	.05	0.0	0.0	0.0	0.0	23.98	69.45	0.0	6.52	0.0	0.0	.05
13/78	466	8.62	0.0	0.0	2.97	0.0	11.7	3.41	0.0	70.59	2.71	0.0	11.59
	467	.07	0.0	0.0	0.0	0.0	99.93	0.0	0.0	0.0	0.0	0.0	.07
	468	.03	0.0	0.0	0.0	0.0	13.46	23.19	0.0	63.32	0.0	0.0	.03
13/79	686	9.49	0.0	13.2	1.79	0.0	8.08	0.0	0.0	65.75	1.69	1.39	24.48
	687	4.02	0.0	0.0	1.38	0.0	78.02	2.50	0.0	13.41	0.66	0.0	5.40
	688	2.79	0.0	0.0	0.0	0.0	86.1	1.09	0.0	10.02	0.0	0.0	2.79
	689	0.10	0.0	0.0	0.0	0.0	0.0	99.9	0.0	0.0	0.0	0.0	.1
13/81	470	3.61	0.0	0.0	2.38	0.0	10.2	0.0	0.0	81.63	2.18	0.0	5.99
	471	.12	0.0	0.0	0.0	0.0	86.08	3.67	0.0	10.13	0.0	0.0	.12
	472	.15	0.0	0.0	0.0	0.0	78.55	9.13	0.0	12.16	0.0	0.0	.15
13/82	683	11.05	.99	6.16	2.39	0.0	25.21	0.0	0.0	51.02	3.18	.56	20.59
	684	1.15	0.0	0.0	0.0	0.0	90.3	0.0	0.0	8.55	0.0	0.0	1.15
13/83	473	12.01	0.0	0.0	0.0	0.0	66.29	13.11	0.0	8.59	0.0	0.0	12.01
15/ 2	366	12.53	2.17	0.0	2.85	0.0	0.0	0.0	0.0	78.22	4.22	0.0	17.55
	367	6.0	3.8	40.17	2.76	0.0	0.0	0.0	0.0	45.05	2.22	6.7	52.73
15/5	680	10.11	0.0	21.68	2.47	0.0	0.55	0.0	0.0	63.26	1.92	2.14	34.26
	681	4.49	1.96	22.58	1.4	0.0	0.0	0.0	0.0	67.83	1.74	5.03	30.43
15/6	673	10.72	0.0	0.0	0.0	0.0	70.6	0.0	0.0	17.3	1.38	0.0	10.72
	674	22.4	5.37	7.74	6.66	0.0	0.0	0.0	0.0	54.5	3.33	.35	42.17
	675	6.35	0.0	79.11	5.85	0.0	0.0	0.0	0.0	7.06	1.64	12.46	91.31
	676	3.65	2.74	46.11	2.29	0.0	0.0	0.0	5.74	38.91	.56	12.63	54.79
	677	3.98	1.69	43.82	.79	0.0	0.0	0.0	3.71	44.33	1.68	11.01	50.28
15/9	251	13.97	1.6	0.0	6.93	0.0	6.86	0.0	0.0	65.72	4.92	0.0	22.5
	252	8.08	1.36	9.35	2.51	0.0	0.0	0.0	0.0	74.34	4.35	1.16	21.3
15/10	256	12.4	1.94	0.0	3.19	0.0	3.32	0.0	0.0	73.11	6.05	0.0	17.53
	257	9.42	.93	0.0	2.08	0.0	0.0	0.0	0.0	83.7	3.81	0.0	12.43
	258	9.61	2.4	0.0	2.24	0.0	1.44	0.0	2.93	77.74	3.63	0.0	14.25
15/11	250	13.74	4.89	0.0	4.3	0.0	7.14	0.0	0.0	62.52	7.41	0.0	22.93
	261	12.82	2.1	0.0	3.08	0.0	15.23	0.0	0.0	61.16	5.61	0.0	18.0
15/12	263	10.33	2.24	10.53	2.03	0.0	0.0	0.0	0.0	72.48	2.38	1.02	25.13
	265	7.62	2.23	11.67	1.57	0.0	0.0	0.0	0.0	74.85	2.07	1.53	23.09
	266	5.11	3.26	61.37	2.25	0.0	0.0	0.0	6.63	18.73	2.65	12.01	71.99
	267	5.3	2.29	28.81	.71	0.0	0.0	0.0	2.57	57.57	2.74	5.44	37.11
	268	6.39	2.56	30.33	1.45	0.0	0.0	0.0	0.03	51.65	2.59	4.75	38.73
15/13	394	5.95	1.55	0.0	2.44	0.0	18.0	0.0	0.0	68.75	3.31	0.0	9.94
	395	6.42	2.41	35.99	1.84	0.0	2.88	0.0	0.0	47.09	3.37	5.61	46.66
	396	5.53	1.34	16.27	1.63	0.0	0.0	0.0	1.1	72.34	1.78	2.94	24.77
15/14	474	3.75	0.0	0.0	1.79	0.0	33.26	0.77	0.0	58.03	2.41	0.0	5.54
	475	4.71	1.7	36.69	1.35	0.0	2.89	0.0	2.29	49.16	1.21	7.79	44.45
	476	5.33	1.11	20.34	1.49	0.0	2.97	0.0	3.72	48.59	3.45	3.82	31.27
	477	5.47	4.83	43.65	3.15	0.0	0.0	0.0	4.76	34.48	3.67	7.98	57.1
15/15	397	5.76	1.74	39.12	1.44	0.0	1.94	0.0	2.6	44.76	2.63	6.79	48.06
	399	4.9	2.67	60.2	1.53	0.0	7.42	0.0	6.25	15.37	1.66	12.29	69.12
	398	4.46	2.14	37.36	1.28	0.0	0.0	0.0	2.17	50.93	1.65	8.38	45.24
15/16	478	2.25	0.0	0.0	1.11	0.0	28.52	25.07	0.0	40.31	2.74	0.0	3.36
	479	6.62	1.88	0.0	2.68	.17	23.74	11.88	3.86	44.95	4.22	0.0	11.35
	480	4.15	1.25	41.0	1.59	0.0	10.81	0.0	2.6	37.8	.7	9.88	47.99
	481	2.18	3.26	51.58	.71	0.0	0.0	0.0	5.9	32.05	4.23	23.66	57.73
	482	4.24	6.56	56.95	2.44	0.0	0.0	0.0	6.02	22.46	1.33	13.43	70.19
	484	6.82	1.86	15.95	2.09	0.0	0.0	0.0	1.03	68.27	4.18	2.34	26.72
15/17	400	5.87	0.0	0.0	2.96	.1	75.0	0.0	4.95	8.82	2.39	0.0	8.93
	401	5.1	2.45	56.99	2.34	.3	8.11	.84	5.57	17.18	1.12	11.17	73.18
	402	4.78	1.82	37.37	1.73	0.0	8.79	0.0	0.0	44.09	1.43	7.82	45.70
	403	3.67	2.03	12.5	1.95	0.0	0.0	0.0	3.81	74.81	1.23	3.41	19.15
	404	4.51	2.69	32.66	1.85	0.0	0.0	0.0	1.53	53.03	3.73	7.24	41.71
15/18	406	1.86	0.0	0.0	0.0	0.0	84.23	0.0	6.17	6.71	1.03	0.0	1.86
	407	3.91	1.47	39.95	1.4	0.0	0.0	0.0	0.0	52.03	1.23	10.22	46.73
	408	3.93	1.65	31.05	1.13	0.0	0.0	0.0	1.9	58.35	2.0	7.9	37.76
	409	5.65	1.91	16.47	1.55	0.0	0.0	0.0	0.0	73.09	1.33	2.92	25.58
15/19	486	9.58	0.0	0.0	0.0	0.0	67.25	0.56	0.0	22.29	0.32	0.0	9.58
	487	4.0	0.0	0.0	0.0	0.0	94.5	0.0	0.0	1.5	0.0	0.0	4.0
	489	5.5	0.0	0.0	0.0	0.0	70.09	0.0	0.0	23.11	1.3	0.0	5.5
15/22	414	2.37	1.99	38.05	1.56	0.0	0.0	0.0	5.19	49.53	1.31	16.05	43.97
	410	15.54	0.0	0.0	5.47	0.0	3.34	30.3	0.0	42.33	3.02	0.0	21.01
	411	12.14	0.0	0.0	3.24	0.0	79.5	0.11	0.0	5.02	0.0	0.0	15.38
	412	59.02	0.0	0.0	7.74	0.0	22.83	0.0	0.0	10.42	0.0	0.0	66.76
	413	8.22	1.36	76.05	5.04	0.0	0.0	0.0	0.0	7.87	1.47	9.25	90.67
15/24	17.038	6.33	2.12	38.75	2.02	0.0	0.0	0.0	2.52	46.26	1.99	6.12	59.22
	17.039	5.43	2.61	65.59	1.87	0.0	0.0	0.0	2.63	20.79	1.08	12.08	75.5
	17.040	5.68	1.12	20.4	1.56	0.0	0.0	0.0	1.05	68.74	1.46	3.59	28.76
15/25	801	3.42	.51	17.94	.94	0.0	5.87	0.0	.98	69.7	.64	5.25	22.81
	802	3.38	2.01	59.92	1.94	0.0	0.0	0.0	0.0	31.69	1.06	17.73	67.25
	803	23.12	0.0	0.0	2.48	0.0	.97	0.0	3.13	63.9	6.4	0.0	25.6
15/26	17.042	5.48	2.19	34.33	1.03	0.0	0.0	0.0	2.18	52.89	1.89	6.26	43.03
	17.043	5.75	.76	32.63	1.04	0.0	0.0	0.0	3.06	59.49	1.36	5.73	36.09
	17.044	6.6	8.09	66.83	1.72	0.0	0.0	0.0	4.69	52.51	2.22	5.68	40.57
15/27	804	4.1	0.0	0.0	3.43	0.0	19.31	0.0	3.7	13.06	0.0	10.13	83.24
	805	5.84	2.11	29.89	1.68	0.0	7.44	0.0	0.0	70.63	2.53	0.0	7.53
	806	4.59	2.56	25.99	1.4	0.0	12.83	0.0	2.23	49.49	3.55	5.12	38.52
	807	5.36	2.92	49.82	1.11	0.0	0.0	0.0	1.74	37.23	1.82	9.29	59.21
15/28	17.045	8.38	.85	8.4	2.07	0.0	1.33	0.0	0.0	75.54	3.43	1.0	19.7
	17.046	7.34	0.0	9.49	1.67	0.0	0.0	0.0	0.0	80.03	1.46	1.29	18.5
15/31	17.048	7.21	3.47	47.59	2.07	0.0	0.0	0.0	11.45	26.99	1.21	6.6	60.34

## APPENDIX II

### Sieve Analysis and Statistical Parameters

The results are expressed in  $\phi$  (phi) .

M,M = Method of Moments, F.M = Folk's Method, I.M = Inman's Method, S&C = Silt & Clay

			MEAN			MEDIAN		STANDARD DEV.			SORTING		SKEWNESS			KURTOSIS				
Pit	Sample	Mode M.M.	M.M.	F.M.	I.M.	F.M.	I.M.	M.M.	F.M.	I.M.	F.M.	I.M.	M.M.	F.M.	I.M.	M.M.	F.M.	I.M.	Grav. %	Soc. %
11/22	6/1073	1.74	1.66	1.66	1.66	1.66	1.66	.97	.91	.83	.91	.83	.08	.05	.00	.86	1.2	.94		4.04
	1072	1.74	2.02	2.0	2.02	1.97	1.97	.87	.89	.97	.39	.97	.03	.04	.04	-.92	.74	.36		1.08
11/23	1076	4.24	2.6	2.69	2.66	2.76	2.76	1.28	1.31	1.42	1.31	1.42	-.25	-.17	-.07	-.63	.73	.39		26.69
	1075	1.74	2.29	2.33	2.33	2.33	2.33	.83	.81	.81	.81	.81	-.05	-.05	.01	-.58	.85	.63		2.2
11/25	1079	4.24	2.66	2.81	2.82	2.8	2.8	1.24	1.22	1.26	1.22	1.26	-.37	-.14	.01	.2	.77	.56		25.94
	1078	3.0	2.63	2.66	2.62	2.75	2.75	.59	.56	.57	.56	.57	-.31	-.26	-.24	.76	1.03	.62		1.21
11/26	1082	4.24	2.6	2.77	2.76	2.80	2.80	1.19	1.21	1.27	1.21	1.27	-.31	-.16	-.04	-.02	.96	.49		20.32
	1081	3.0	2.52	2.56	2.54	2.61	2.61	.66	.55	.52	.55	.52	-.68	-.15	-.14	3.77	1.09	.79		.61
11/27	1085	1.74	1.54	1.56	1.59	1.51	1.51	1.39	1.46	1.51	1.46	1.51	.16	.08	.05	-.77	.93	.54	5.89	15.09
	1084	3.0	2.82	2.91	2.93	2.87	2.87	.89	.83	.79	.83	.79	-.53	-.03	.06	2.65	1.24	.8		7.02
11/28	1093	-1.04	1.22	1.02	.76	1.55	1.55	1.85	2.3	2.52	2.3	2.52	-.002	-.29	-.31	-1.41	.74	.36		7.63
	1092	-1.04	.87	.83	.89	.70	.70	1.45	1.59	1.67	1.59	1.67	.22	.11	.12	-.64	.98	.5		1.1
	1091	1.74	1.94	1.91	1.86	2.01	2.01	1.32	1.39	1.41	1.39	1.41	-.12	-.1	-.11	-.73	.93	.6	7.95	15.59
	1090	1.0	1.14	1.1	1.18	.94	.94	.9	.86	.85	.86	.85	.39	.33	.29	.68	.99	.68		1.05
	1089	3.0	2.98	3.0	2.98	3.04	3.04	.69	.59	.48	.59	.48	-.75	-.12	-.13	5.64	1.64	1.46		9.33
	1088	3.47	2.61	2.65	2.55	2.84	2.84	1.07	1.0	.94	1.0	.94	-.46	-.29	-.31	1.0	1.0	.86		10.26
13/1	1097	3.0	2.31	2.18	1.86	2.82	2.82	1.7	2.06	2.16	2.06	2.16	-.51	-.51	-.44	-.17	1.71	.5		20.2
	1096	-1.04	1.05	.85	.66	1.23	1.23	1.6	1.97	2.16	1.97	2.16	-.04	-.27	-.26	-1.32	.79	.37		1.29
	1094	4.24	2.86	2.95	2.98	2.9	2.9	1.03	1.01	1.07	1.01	1.07	-.38	-.05	-.08	.64	.79	.46	4.93	26.06
13/2	1101	-1.04	1.75	1.62	1.43	2.0	2.0	1.53	1.84	1.67	1.84	1.67	-.27	-.35	-.34	-.5	1.48	.98		9.03
	1100	-1.04	.98	-.41	-1.36	1.48	1.48	1.9	4.01	4.33	4.01	4.33	.03	-.62	-.65	-1.56	.78	.4		6.43
	1099	3.0	2.43	2.44	2.42	2.49	2.49	.67	.61	.56	.61	.56	-.48	-.2	-.13	2.84	1.19	.93		1.67
13/3	1106	-1.04	.89	.77	.92	.47	.47	1.7	1.84	1.98	1.84	1.98	.21	.25	.23	-1.12	.76	.42		7.02
	1105	3.0	2.59	2.61	2.57	2.68	2.68	.6	.55	.54	.55	.54	-.27	-.21	-.21	1.36	1.09	.72		2.31
	1104	4.24	3.11	3.1	3.02	3.27	3.27	1.08	1.04	1.12	1.04	1.12	-.4	-.32	-.23	-.2	.75	.39		43.09
	1103	3.0	2.13	2.11	2.01	2.3	2.3	1.02	1.02	1.02	1.02	1.02	-.2	-.23	-.28	-.16	1.02	.67	3.66	8.24
13/16	1141	3.0	2.25	2.28	2.27	2.31	2.31	.88	.86	.85	.86	.85	-.11	-.09	-.06	-.35	.93	.67		3.09
13/17	1138	1.74	1.64	1.67	1.72	1.58	1.58	.97	1.01	1.09	1.01	1.09	.21	.14	.13	-.51	.91	.43		1.3
13/18	1136	.49	1.38	1.45	1.75	.84	.84	1.24	1.26	1.46	1.26	1.46	.37	.59	.62	-1.01	.62	.2		.54
13/27	1120	1.0	.96	.93	.94	.9	.9	.53	.46	.44	.46	.44	.75	.12	.09	4.63	1.24	.79		.06
	1119	3.0	2.61	2.66	2.62	2.75	2.75	.63	.55	.54	.55	.54	-.5	-.25	-.23	2.4	1.11	.75		1.6
13/28	1116	.49	1.4	1.4	1.56	1.08	1.08	1.12	1.15	1.28	1.15	1.28	.24	.37	.38	-.98	.72	.31		.61
13/29	1128	.49	1.53	1.5	1.68	1.13	1.13	1.21	1.21	1.39	1.21	1.39	.17	.37	.39	-1.35	.6	.23		0.32
13/33	1148	-1.04	.68	-.84	-1.88	1.21	1.21	1.62	3.85	4.24	3.85	4.24	-.02	-.72	-.73	-1.67	.75	-.35		.35
	1149	-1.04	.61	.52	.40	.77	.77	1.04	1.25	1.21	1.25	1.21	-.08	-.37	-.31	-.3	1.21	.75		.32
13/34	1151	2.0	1.52	1.49	1.41	1.66	1.66	.82	.76	.73	.76	.73	-.09	-.3	-.34	1.17	1.22	.78		1.08
	1150	-1.04	.41	-.81	-1.57	.7	.7	1.36	3.11	3.39	3.11	3.39	.04	-.67	-.67	-1.38	.79	.38		0.31
13/35	1154	1.74	1.75	1.75	1.78	1.7	1.7	.7	.63	.57	.63	.57	-.05	.14	.14	2.3	1.38	1.07		.29
	1153	1.74	0.8	.71	.53	1.07	1.07	1.06	1.29	1.18	1.29	1.18	-.27	-.5	-.45	-.35	1.4	.97		0.18
13/36	1157	1.74	1.63	1.65	1.7	1.55	1.55	.94	.92	.88	.92	.88	.09	.14	.17	.4	1.17	.78		2.08
	1156	3.0	2.18	2.23	2.24	2.2	2.2	.94	.84	.87	.84	.87	-.34	-.01	.05	1.26	.81	.52		2.54
	1155	3.0	2.54	2.58	2.48	2.76	2.76	.79	.77	.79	.77	.79	-.41	-.37	-.35	.48	.98	.58		1.34
13/37	1110	1.0	1.68	1.71	1.79	1.56	1.56	.89	.92	1.0	.92	1.0	.13	.2	.24	-.38	.8	.38		0.0
13/38	1125	1.0	1.8	1.79	1.82	1.72	1.72	1.06	1.08	1.2	1.08	1.2	.03	.07	.08	-1.04	.7	.34		1.01
	1124	1.74	2.1	2.07	2.1	2.03	2.03	.87	.87	.9	.87	.9	.03	.07	.08	-.31	.95	.56		2.24
	1123	1.74	2.0	1.96	1.96	1.95	1.95	1.14	1.2	1.26	1.2	1.26	.03	.05	.02	-.95	.81	.49		6.15
13/39	362	3.0	2.11	2.12	2.05	2.27	2.27	.96	.99	1.09	.99	1.09	-.14	-.21	-.21	-1.12	.74	.35		.03
	364	3.0	2.13	2.15	2.1	2.26	2.26	.94	.96	1.05	.96	1.05	-.11	-.17	-.15	-1.05	.75	.38		.39
13/40	359	3.0	2.62	2.64	2.62	2.7	2.7	.49	.49	.49	.49	.49	-.27	-.18	-.18	.31	1.01	.65		
13/41	358	3.0	2.44	2.43	2.43	2.44	2.44	.6	.58	.61	.58	.61	-.19	-.02	-.02	-.07	.87	.53		.02
13/42	1131																			
	1130	3.0	2.46	2.51	2.53	2.45	2.45	.77	.57	.59	.57	.59	-.94	.11	.14	7.91	.92	.57		1.75
13/43	355	2.0	2.1	2.13	2.17	2.06	2.06	.63	.6	.63	.6	.63	-.26	.17	.18	2.78	.93	.51		.01
13/44	369																			
	370																			
13/45	373																			

Pit	Sample	Mode M.M.	MEAN			MEDIAN		STANDARD DEV.			SORTING		SKEWNESS			KURTOSIS			Grav. %	Sec. %
			M.M.	F.M.	I.M.	F.M.	I.M.	M.M.	F.M.	I.M.	F.M.	I.M.	M.M.	F.M.	I.M.	M.M.	F.M.	I.M.		
13/75	455	3.0	2.55	2.37	2.35	2.41	2.41	1.01	1.02	.98	1.02	.98	-.17	-.06	-.06	-.13	1.04	.79		7.58
	456	3.0	2.29	2.3	2.28	2.32	2.32	.97	.99	.98	.99	.98	-.04	-.002	-.03	-.49	.99	.71		6.63
	457	1.74	2.07	2.09	2.18	1.9	1.9	1.14	1.2	1.24	1.2	1.24	.14	.2	.22	-.4	1.2	.54		13.44
	458	2.0	1.95	1.97	2.0	1.92	1.92	1.27	1.33	1.37	1.33	1.37	-.04	.03	.05	-.75	.92	.56	3.91	11.23
13/76	459	3.0	2.39	2.39	2.35	2.46	2.46	.87	.88	.8	.88	.8	-.19	-.08	-.13	.43	1.15	.96		5.48
	460	3.0	2.25	2.26	2.23	2.31	2.31	.92	.93	.9	.93	.9	-.11	-.08	-.09	-.18	1.02	.77		4.5
	461	3.97	2.3	2.37	2.34	2.42	2.42	1.29	1.34	1.46	1.34	1.46	-.25	-.16	-.06	-.69	.8	.38	4.3	4.3
13/77	463	4.24	2.31	2.34	2.37	2.28	2.28	1.05	1.06	1.05	1.06	1.05	-.01	.07	.09	-.34	1.06	.68		12.58
	464	4.24	2.12	2.2	2.2	2.22	2.22	1.47	1.59	1.79	1.59	1.79	-.13	-.08	-.01	-.97	.81	.29	2	18.54
	465	-1.04	.43	-1.29	-1.41	-1.05	-1.05	2.0	4.2	4.77	4.2	4.77	.43	-.1	-.07	-.89	.72	.26		13.84
13/78	466	3.0	2.29	2.31	2.28	2.36	2.36	.82	.79	.79	.79	.79	-.25	-.13	-.1	.42	.93	.65		1.37
	467	1.74	1.9	1.91	1.93	1.86	1.86	1.17	1.22	1.21	1.22	1.21	-.02	.05	.06	-.52	1.0	.69		5.22
	468	-1.04	.35	-1.57	-2.01	-.68	-.68	1.77	4.11	4.72	4.11	4.72	.39	-.27	-.3	-.78	.76	.39		6.18
13/79	686	1.74	2.16	2.32	2.54	1.89	1.89	1.13	1.27	1.45	1.27	1.45	.19	.35	.45	-.5	1.11	.25		17.0
	687	-1.04	.55	.08	.19	-.13	-.13	1.87	2.52	2.76	2.52	2.76	.37	.13	.12	-.85	.82	.35		11.0
	688	1.74	1.65	1.63	1.64	1.62	1.62	1.32	1.41	1.42	1.41	1.42	.05	.04	.01	-.67	1.07	.62	4.04	10.2
	689	4.24	2.13	.72	-.93	4.0	4.0	2.41	4.7	5.09	4.7	5.09	-.25	-.97	-.97	-1.64	.85	.4		59.03
13/81	470	4.24	2.52	2.67	2.77	2.46	2.46	1.08	1.13	1.24	1.13	1.24	-.15	.13	.25	.07	1.01	.36		19.31
	471	-1.04	.7	.52	.8	-.04	-.04	1.97	2.53	2.94	2.53	2.94	.34	.24	.29	-1.06	.74	.19		14.94
	472	-1.04	1.19	.97	.92	1.08	1.08	1.91	2.55	2.85	2.55	2.85	.1	-.11	-.05	-1.34	.83	0.31		14.87
13/82	683	1.74	2.21	2.26	2.33	2.11	2.11	1.0	.94	.84	.94	.84	.03	.21	.26	.23	1.16	1.02		10.1
	684	1.74	1.71	1.69	1.68	1.7	1.7	1.26	1.35	1.36	1.35	1.36	.02	.02	.01	-.09	.99	.61	3.06	8.5
13/83	473	4.24	2.39	2.49	2.34	2.78	2.78	1.5	1.52	1.7	1.52	1.7	-.23	-.31	-.26	-1.06	.67	.3	5.8	26.67
15/2	366	1.74	1.39	1.87	1.84	1.94	1.94	1.31	1.4	1.39	1.4	1.39	-.19	-.09	-.08	-.59	1.04	.66	5.29	10.9
	367	-1.04	.93	-1.66	-3.28	1.59	1.59	1.64	5.53	5.72	5.53	5.72	-.08	-.83	-.85	-1.41	1.07	.54		1.19
15/5	680	1.0	.75	.75	.73	.81	.81	.65	.59	.52	.59	.52	.05	-.16	-.16	1.47	1.27	1.08		3.53
	681	-1.04	.77	.48	.27	.91	.91	1.3	1.68	1.64	1.62	1.64	-.001	-.33	-.39	-.82	1.18	.72		1.15
15/6	673	1.74	1.36	1.33	1.41	1.19	1.19	1.17	1.17	1.19	1.17	1.19	.22	.2	.18	-.32	.93	.58		3.87
	674	1.74	2.35	2.36	2.34	2.41	2.41	1.1	1.13	1.18	1.13	1.18	-.17	-.07	-.05	-.43	.89	.51		6.46
	675	4.24	2.33	2.33	2.11	2.77	2.77	1.79	1.74	2.02	1.74	2.02	-.18	-.36	-.33	-1.47	.57	.81	4.91	43.57
	676	-1.04	1.76	1.45	1.03	2.29	2.29	1.62	2.15	2.02	2.15	2.02	-.36	-.58	-.62	-.64	1.52	.86		6.96
	677	-1.04	-.42	-2.99	-3.14	-2.7	-2.7	1.14	3.61	4.08	3.61	4.08	.73	-.13	-.11	1.45	.67	.27		.69
15/9	251	3.0	2.43	2.46	2.43	2.54	2.54	.74	.73	.74	.73	.74	-.41	-.21	-.15	1.15	.95	.16		.69
	252	2.0	2.1	2.09	2.1	2.05	2.05	.48	.44	.44	.44	.44	.14	.19	.12	2.7	1.0	.66		.33
15/10	256	3.0	2.3	2.38	2.31	2.53	2.53	1.09	1.02	.98	1.02	.98	-.51	-.3	-.23	.99	1.05	.79		3.02
	257	1.74	1.98	1.98	2.02	1.91	1.91	.6	.59	.59	.59	.59	.09	.16	.17	.28	1.02	.66		.02
	258	1.74	1.71	1.71	1.73	1.67	1.67	.54	.41	.3	.41	.3	.17	.12	.18	4.22	1.98	1.86		.56
15/11	260	3.0	2.57	2.61	2.5	2.81	2.81	.93	.92	.9	.92	.9	-.14	-.33	-.35	.47	.99	.71		4.3
	261	3.0	2.37	2.38	2.29	2.57	1.08	1.08	1.08	1.1	1.08	1.1	-.27	-.24	-.26	-.38	.91	.65		5.67
	262	1.74	1.48	1.45	1.45	1.45	1.45	.63	.60	.57	.60	.57	.1	.07	.002	1.37	1.17	.87		0.0
15/12	265	-1.04	1.02	.97	.85	1.2	1.2	1.37	1.52	1.54	1.52	1.54	-.04	-.21	-.23	-1.02	.95	.62		.02
	266	3.0	2.85	2.86	2.86	2.86	2.86	.07	.1	.1	.1	.1	-3.7	-.13	0.0	0.0	1.0	.79		0.0
	267	1.49	1.11	1.13	1.12	1.14	1.14	.42	.33	.32	.33	.32	-.69	-.06	-.04	9.45	.98	.77		.01
	268	1.49	1.12	1.12	1.12	1.13	1.13	.46	.37	.35	.37	.35	-.17	-.06	-.03	6.43	1.05	.91		.01
15/13	394	4.24	1.87	1.87	1.79	2.04	2.04	1.64	1.93	1.89	1.93	1.89	-.22	-.24	-.13	-.76	1.18	.72		14.91
	395	4.24	3.03	3.08	2.89	3.45	3.45	1.23	1.13	1.25	1.13	1.25	-.43	-.49	-.44	-.03	.63	.31		46.3
	396	1.74	2.09	2.17	2.38	1.74	1.74	.98	.94	.88	.94	.88	.43	.59	.73	.26	1.69	.87	2.12	15.21
15/14	474	4.24	1.5	1.65	1.67	1.61	1.61	1.72	2.01	2.31	2.01	2.31	.01	-.04	.02	-1.07	.86	.22		16.93
	475	4.24	2.51	2.58	2.61	2.54	2.54	1.44	1.39	1.5	1.39	1.5	-.24	-.08	.04	-.63	.68	.4		32.58
	476	1.74	1.90	1.89	2.0	1.69	1.69	1.15	1.16	1.15	1.16	1.15	.23	.27	.27	-.29	1.13	.68		14.75
	477	-1.04	.72	.29	-.06	.99	.99	1.63	2.24	2.4	2.24	2.4	.11	-.36	-.44	-1.17	.79	.44		3.6
15/15	397	1.74	-.65	-1.62	-1.52	-1.81	-1.81	.98	1.71	1.78	1.71	1.78	1.11	.22	.16	4.47	1.01	.52		.1
	399	-1.04	.93	.69	.29	1.5	1.5	1.18	1.63	1.47	1.63	1.47	-.29	-.76	-.82	-.48	1.73	1.01		.1
	398	1.74	1.31	1.29	1.17	1.53	1.53	.74	.62	.57	.62	.57	.74	.62	.57	-.05	-.5	-.64	5.52	6.55
15/16	478	4.24	2.63	2.67	2.66	2.7	2.7	1.31	1.29	1.44	1.29	1.44	-.15	-.11	-.02	-1.11	.63	.3	4.48	35.4
	479	4.24	2.71	2.78	2.55	3.25	3.25	1.5	1.4	1.6	1.4	1.6	-.24	-.48	-.44	-1.22	.61	.23	4.16	49.45
	480	-1.04	.81	.57	.37	.96	.96	1.5	1.9	2.04	1.9	2.04	.04	-.26	-.29	-1.18	.86	.44		0.43
	481	1.49	1.82	1.9	1.94	1.83	1.83	1.09	1.12	1.14	1.12	1.14	-.08	.02	.09	-.43	.94	.61		0.66
	482	1.74	1.79	1.73	1.65	1.9	1.9	1.56	1.8	1.74	1.8	1.74	-.22	-.22	-.15	-.75	1.12	.76		7.8
	484	2.0	1.93	1.97	1.99	1.95	1.95	.63	.54	.44	.54	.44	-.41	-.02	.08	3.11	1.41	1.41	3.61	3.65
15/17	400	4.24	1.26	1.13	1.29	.81	.81	2.17	2.35	2.79	2.35	2.79	.11	.13	.17	-1.62	.51	.12		18.19
	401	-1.04	.62	.37	.33	.44	.44	1.49	1.68	1.67	1.68	1.67	.33	.01	-.07	-.06	.98	.67		2.4
	402	-1.04	.05	-3.12	-3.55	-2.27	-2.27	1.6	4.77	5.17	4.77	5.17	.52	-.22	-.25	-.05	.72	.39		3.91
	403	1.74	1.54	1.59	1.57	1.62	1.62	.56	.44	.41	.44	.41	-1.02	-.19	-.14	7.83	1.19	.91		.01
15/18	404	-1.04	.46	-.19	-.67	.74	.74	1.39	2.24	2.43	2.24	2.43	.04	-.54	-.57	-1.37	.76	.4		.06
	406	-1.04	-.44	-.96	-.85	-1.19	-1.19	1.16	1.5	1.48	1.5	1.48	.9	.31	.23	2.39	1.13	.69		.08
	407	1.74	.81	.66	.43	1.12	1.12	1.09	1.22	1.26	1.22	1.26	-.3	-.56	-.56	.5	1.1	.55		.04
	408	1.74	.94	.93	.83	1.14	1.14	1.02	1.14	.88	1.14	.88	-.32	-.49	-.35	.48	1.65	1.62		.72
	409	1.74	1.42	1.44	1.36	1.58	1.58	.53	.45	.44	.45	.44	-.97	-.47	-.5	6.16	1.04	.69		.003
15/19	486																			

### APPENDIX III

#### Chemical Analysis of the Sediments

(The oxides are expressed as percentages and  
the elements are expressed as parts per million)

The digestion used for these analyses consisted of attack by 50% nitric acid, this will not have dissolved all the minor mineral phases or quartz.

This means that the values quoted for Zr, Ba, TiO₂ and possibly strontium will not be whole rock values...

Pit	Sample	CO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	TiO ₂	MnO	Sr	Cu	Zr	Cr	Ba
11/22	6/1073	15.39	19.44	.33	.13	1.38	.13	.03	0.0	0.0	>2,000	1.0	0.0	99.0	5.0
	1072	8.54	9.67	.34	.14	1.25	.02	.02	.01	0.0	321.0	1.0	0.0	70.0	8.0
11/23	1076	3.69	8.34	.72	.48	5.24	.04	.06	.01	.01	1,528	3.0	0.0	81.0	16.0
	1075	7.0	8.88	.41	.19	1.36	.04	.03	.01	.01	>2,000	1.0	0.0	97.0	59.0
11/25	1079	5.68	8.9	.87	.61	5.29	.11	.06	.02	.01	7,000	4.0	1.0	104.0	46.0
	1078	6.38	7.15	.92	.31	1.22	.12	.13	.02	0.0	343.0	2.0	2.0	64.0	38.0
11/26	1082	7.96	14.95	.85	.59	3.51	.08	.06	.02	.01	243.0	4.0	1.0	111.0	43.0
	1081	6.96	7.84	.59	.28	1.09	.06	.06	.01	.01	>2,000	2.0	1.0	62.0	27.0
11/27	1085	13.78	29.68	.41	.19	1.66	.11	.02	0.0	0.0	201.0	2.0	0.0	114.0	4.0
	1084	34.06	38.9	.26	.04	.89	.2	.12	0.0	0.0	>2,000	4.0	3.0	153.0	0.0
11/28	1093	35.27	41.0	.33	.09	2.13	.31	.02	0.0	0.0	>2,000	2.0	0.0	122.0	0.0
	1092	33.28	34.49	.18	.01	1.72	.26	0.0	0.0	0.0	>2,000	1.0	0.0	105.0	0.0
	1091	26.63	31.38	.36	.15	2.07	.21	.02	.01	0.0	>2,000	2.0	0.0	108.0	0.0
	1090	11.71	12.86	.15	.01	.79	.06	.01	0.0	0.0	1,316	0.0	0.0	74.0	0.0
	1089	10.19	13.32	.75	.4	3.35	.11	.07	.02	.01	440.0	2.0	1.0	73.0	18.0
	1088	15.64	18.18	.59	.32	1.59	.13	.05	.02	.01	>2,000	2.0	1.0	93.0	11.0
13/1	1097	40.3				2.66					17,200				
	1096	34.2	36.83	.2	.01	1.6	.26	0.0	0.0	0.0	>2,000	2.0	0.0	117.0	0.0
	1094	18.81	20.77	.57	.36	1.86	.14	.04	.01	0.0	>2,000	3.0	1.0	86.0	9.0
13/2	1101	20.0	26.5	.33	.11	3.49	.12	.02	0.0	0.0	1,667	1.0	0.0	91.0	0.0
	1100	20.52	26.11	.31	.15	2.37	.16	.02	.01	0.0	>2,000	1.0	1.0	128.0	0.0
	1099	5.74	4.74	.27	.12	.75	.02	.04	.01	0.0	104.0	1.0	1.0	76.0	4.0
13/3	1106	1.41	17.46	.25	.09	1.8	.02	.01	0.0	0.0	>2,000	1.0	1.0	111.0	0.0
	1105	6.36	8.56	.68	.33	2.33	.06	.07	.02	.01	1,564	2.0	1.0	119.0	39.0
	1104	5.8	12.9			5.58					12,300				
	1103	8.48	8.91	.68	.41	3.44	.05	.07	.02	.01	>2,000	3.0	1.0	138.0	37.0
13/16	1141	5.98	8.27	.41	.19	1.39	.03	.05	.01	0.0	146.0	2.0	1.0	78.0	15.0
13/17	1138	8.66	12.66	.22	.03	.73	.02	.02	0.0	0.0	724.0	1.0	0.0	66.0	3.0
13/18	1136	11.41	14.3	.2	.06	.82	.02	.03	0.0	0.0	504.0	1.0	1.0	67.0	1.0
13/27	1120	4.0	4.77	.08	0.0	.37	0.0	.01	0.0	0.0	112.0	0.0	0.0	65.0	0.0
	1119	5.37	6.84	.49	.24	1.02	0.04	.08	.01	0.0	137.0	2.0	2.0	81.0	19.0
13/28	1116	5.75	8.24	.27	.1	.99	.02	.03	.01	0.0	657.0	1.0	1.0	88.0	3.0
13/29	1128	6.26	11.31	.34	.12	.76	.03	.03	.01	0.0	501.0	1.0	1.0	84.0	12.0
13/33	1148	25.85	33.52	.2	.04	.67	.31	.02	0.0	0.0	>2,000	8.0	0.0	127.0	11.0
	1149	18.44	23.23	.13	.04	.81	.14	.02	0.0	0.0	>2,000	24.0	0.0	124.0	5.0
13/34	1151	17.07	21.8	.43	.25	1.71	.13	.04	0.0	0.0	>2,000	19.0	0.0	139.0	19.0
	1150	15.59	20.75	.18	.02	.63	.12	.01	0.0	0.0	3,500	63.0	0.0	91.0	8.0
13/35	1154	9.0	11.46	.28	.17	.92	.07	.06	0.0	0.0	1,212	28.0	0.0	129.0	16.0
	1153	13.13	16.76	.13	.03	.62	.05	.01	0.0	0.0	1,105	20.0	0.0	100.0	3.0
13/36	1157	11.05	13.23	.29	.18	1.0	.04	.06	0.0	0.0	578.0	21.0	0.0	123.0	11.0
	1156	11.08	12.7	.44	.29	1.01	.05	.06	0.0	0.0	451.0	15.0	0.0	119.0	19.0
	1155	7.61	8.34	.57	.33	1.25	.05	.08	.01	.01	183.0	40.0	1.0	106.0	36.0
13/37	1110	5.19	12.51	.28	.15	.89	.03	.01	0.0	0.0	581.0	8.0	0.0	100.0	16.0
13/38	1125	4.32	12.43	.23	.06	.8	.01	.01	0.0	0.0	608.0	0.0	0.0	78.0	1.0
	1124	4.84	19.75	.26	.09	.95	.02	0.0	0.0	0.0	1,332	1.0	0.0	87.0	0.0
	1123	5.41	8.01	.71	.42	1.61	.04	.08	.01	.01	380.0	4.0	0.0	81.0	12.0
13/39	362	7.52	10.54	1.33	1.73	1.15	.23	.26	.03	.01	447.0	52.0	1.0	838.0	83.0
	364	5.99	9.46	.52	.45	1.07	.06	.09	.01	0.0	390.0	111.0	1.0	189.0	29.0
13/40	359	4.52	6.97	.57	.59	1.01	.06	.06	.01	0.0	366.0	46.0	0.0	215.0	46.0
13/41	358	5.68	7.42	.92	1.05	1.06	.14	.19	.02	.01	310.0	77.0	1.0	463.0	53.0
13/42	1131	5.91	8.88	.57	.28	.92	.05	.08	.01	0.0	240.0	2.0	1.0	79.0	28.0
	1130	7.17	8.85	.40	.19	.77	.04	.04	.01	0.0	228.0	1.0	1.0	72.0	15.0
13/43	355	6.58	7.67	.34	.39	.87	.04	.05	0.0	0.0	251.0	69.0	0.0	187.0	25.0
13/44	369	8.53	14.72	.41	.22	1.08	.08	.01	.02	0.0	444.0	2.0	1.0	109.0	10.0
	370	4.27	13.09	.24	.07	1.11	.03	.00	.01	0.0	588.0	0.0	0.0	106.0	0.0
13/45	373	5.14	12.29	.41	.2	1.26	.04	.01	.02	0.0	517.0	1.0	1.0	127.0	10.0
	374	1.45	32.7	.04	.0	.18	.06	.00	.00	0.0	927.0	0.0	0.0	144.0	0.0
	375	0.96	34.35	.04	.0	.37	2.48	.03	.00	0.0	568.0	0.0	0.0	96.0	0.0
13/46	381	9.12	19.0	.3	.11	1.51	.07	0.0	.01	.0	1,570	1.0	0.0	136.0	0.0
	380	1.87	25.14	.09	.0	.67	.05	0.0	.0	.0	722.0	0.0	0.0	131.0	0.0
	378	0.64	32.0	.05	.0	.15	.05	0.0	.0	.0	>2,000	1.0	0.0	170.0	0.0
	379	1.2	32.76	.25	.09	1.79	3.71	.12	.0	.0	>2,000	2.0	0.0	138.0	0.0
13/47	812	25.37	36.86	.67	.36	6.52	.12	.01	.01	0.0	>2,000	1.0	1.0	159.0	0.0
	813	18.43	32.81	.25	.08	1.87	.07	0.0	0.0	0.0	5,300	0.0	0.0	122.0	0.0
	814	.21	30.5	.03	0.0	0.2	.01	0.0	0.0	0.0	6,200	0.0	0.0	136.0	0.0
13/49	384	.62	30.28	.07	.0	.63	.04	.0	.0	.0	3,500	0.0	0.0	141.0	0.0
13/50	696	.82	31.04	.08	0.0	.76	.14	0.0	0.0	0.0	614.0	0.0	0.0	120.0	0.0
13/52	385	.41	13.74	.12	.0	1.09	3.42	.16	.0	.0	6,600	1.0	0.0	129.0	0.0
13/53	386	10.2	19.3	.28	.09	1.07	.1	.01	.0	.0	>2,000	3.0	0.0	100.0	2.0
13/58	1113	7.51	9.79	.75	.49	1.42	.08	.09	.01	.01	628.0	8.0	0.0	166.0	44.0
13/59	353	6.13	8.21	1.36	1.03	1.3	.24	.27	.03	.01	288.0	68.0	2.0	427.0	70.0
13/60	350	8.02	8.74	.4	.14	2.1	.74	.06	.01	0.0	407.0	30.0	0.0	70.0	29.0
	352	7.98	8.08	.4	.37	1.86	.05	.07	0.0	0.0	299.0	76.0	0.0	172.0	24.0
13/61	281	5.05	8.55	.5	.56	1.53	.11	.05	.01	.01	385.0	237.0	0.0	196.0	32.0
	282	6.32	8.26	.73	.63	2.02	.1	.07	.02	.01	446.0	59.0	0.0	216.0	42.0
13/62	286	7.93	9.83	.6	.5	1.73	.13	.08	.01	.01	309.0	29.0	1.0	182.0	34.0
	285	8.09	8.27	.71	.72	1.72	.08	.09	.01	.01	291.0	113.0	0.0	270.0	45.0
13/63	288	4.87	7.85	1.23	1.49	1.76	.21	.23	.03	.01	277.0	37.0	1.0	610.0	69.0
13/64	691	7.64	19.08	.79	.58	5.39	.06	.12	.01	.01	>2,000	5.0	4.0	164.0	2.0
	692	3.15	16.07	.59	.39	3.81	.02	.11	.01	.01	430.0	4.0	3.0	139.0	0.0
	693	0.94	28.94	.26	.1	1.9	.06	.0	.0	.0	4,000	0.0	0.0	155.0	0.0
	694	1.63	29.7			1.34					6,400				
13/70	291	12.25	15.98	.47	.31	1.69	.07	.05	.01	.01	1,015	23.0	1.0	125.0	23.0
	292	13.45	24.54	.29	.59	1.05	.15	.04	0.0	0.0	>2,000	18.0	0.0	304.0	7.0
	293	6.49	10.28	.29	.34	1.2	.03	0.0	0.0	0.0	348.0	32.0	0.0	151.0	20.0
	294	3.13	5.1	.55	.54	1.52	.08	.08	.02	0.0	275.0	34.0	1.0	218.0	36.0
13/72	297	5.47	7.08			1.80					2,100				
	298	2.56	14.25	.33	.17	2.04	.07	.04	0.0	0.0	552.0	129.0	0.0	86.0	4.0
	299	4.0	15.52	.18	.06	1.15	.08	.02	0.0	0.0	703.0	30.0	0.0	85.0	0.0
13/74	450	7.54	10.02	.53	.35	1.32	.09	.04	.01	.01	398.0	38.0	0.0	127.0	30.0
	451	6.55	9.04	.77	.96	2.22	.12	.13	.02	.01	444.0	7.0			

Pit	Sample	CO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	TiO ₂	MnO	Sr	Cu	Zr	Cr	Ba
13/75	455	5.5	11.68	.49	.36	1.87	.09	.03	.01	.01	480.0	17.0	0.0	127.0	25.0
	456	4.63	8.7	.78	.88	2.45	.11	.14	.01	.01	437.0	27.0	1.0	388.0	35.0
	457	0.0	27.42	.11	.0	.65	.18	0.0	0.0	0.0	1,178	41.0	0.0	66.0	0.0
	458	0.0	29.45	.13	.02	.5	.07	0.0	0.0	0.0	3,500	26.0	0.0	123.0	0.0
13/76	459	5.24	8.7	.49	.34	1.35	.09	.04	.01	0.0	414.0	12.0	0.0	116.0	35.0
	460	5.0	10.37	.42	.25	1.81	.06	.03	.01	0.0	482.0	22.0	0.0	94.0	24.0
	461	0.0	22.56	.12	.01	.84	.05	0.0	0.0	0.0	5,300	14.0	0.0	103.0	0.0
13/77	463	4.69	13.29	1.04	1.26	2.79	.12	.13	.02	.01	710.0	47.0	1.0	497.0	42.0
	464	0.0	31.73	.1	0.0	.62	.03	.02	0.0	0.0	8,300	15.0	0.0	92.0	0.0
	465	0.0	24.98	.06	0.0	.34	.07	.02	0.0	0.0	721.0	1.0	0.0	58.0	0.0
13/78	466	4.47	14.06	.89	1.1	2.58	.1	.09	.01	.01	528.0	56.0	0.0	415.0	31.0
	467	0.001	28.56	.06	0.0	.33	.04	.01	0.0	0.0	6,600	8.0	0.0	94.0	0.0
	468	0.0	14.51	.13	.03	.88	.11	0.0	0.0	0.0	6,200	16.0	0.0	87.0	0.0
13/79	686	8.68	14.55	.51	.33	1.8	.06	.12	.01	0.0	881.0	4.0	3.0	151.0	6.0
	687	2.03	28.87	.38	.22	2.72	.02	.08	0.0	0.0	1,394	3.0	2.0	135.0	0.0
	688	1.58	30.72	.13	0.0	.8	.03	.06	0.0	0.0	655.0	2.0	1.0	107.0	0.0
	689	1.44	39.82	.26	.11	1.37	.07	.07	0.0	0.0	460.0	2.0	2.0	135.0	0.0
13/81	470	3.34	29.88	1.87	1.57	3.29	.24	.32	.03	.02	529.0	28.0	2.0	606.0	77.0
	471	.77	27.95	.72	.49	4.57	.07	.04	.01	.01	1,230	38.0	0.0	80.0	8.0
	472	.72	28.95	.3	.12	1.18	.08	.04	0.0	0.0	>2,000	12.0	0.0	152.0	0.0
13/82	683	6.54	15.79	.34	.2	1.14	.02	.08	0.0	0.0	465.0	3.0	2.0	120.0	0.0
	684	1.73	29.35	.13	0.0	.5	.03	.02	0.0	0.0	>2,000	1.0	1.0	153.0	0.0
13/83	473	5.59	28.95	.52	.4	3.34	.07	.06	.01	0.0	913.0	4.0	1.0	127.0	0.0
15/2	366	8.44	8.14	.48	.23	1.22	.04	.07	.02	0.0	233.0	1.0	1.0	136.0	20.0
	367	24.49	27.85	.24	.08	.94	.24	.05	.01	0.0	>2,000	2.0	1.0	183.0	0.0
15/5	680	14.73	17.4	.12	0.0	1.35	.09	.05	0.0	0.0	1,103	2.0	2.0	148.0	6.0
	681	11.68	14.66	.09	0.0	.56	.11	.06	0.0	0.0	988.0	1.0	2.0	110.0	0.0
15/6	673	4.64	26.02	.16	.02	.81	.02	.06	0.0	0.0	1,651	2.0	2.0	122.0	0.0
	674	14.8	12.23			7.66					9,200				
	675	31.39	26.7	.71	.41	2.51	.18	.12	.01	0.0	>2,000	4.0	3.0	137.0	0.0
	676	21.1	25.52	.11	0.0	.68	.15	.04	0.0	0.0	>2,000	1.0	1.0	130.0	0.0
	677	19.54	22.44	.13	0.0	.61	.15	.04	0.0	0.0	>2,000	1.0	2.0	144.0	0.0
15/9	251	7.98	8.05			2.38					3,600				
	252	9.13	8.69	.28	.1	.98	.04	.03	.01	0.0	470.0	1.0	1.0	80.0	2.0
15/10	256	7.17	8.07	.46	.26	1.59	.04	.04	.02	0.0	312.0	2.0	1.0	72.0	7.0
	257	6.82	6.51	.25	.08	.72	.02	.05	0.0	0.0	309.0	1.0	1.0	82.0	5.0
	258	6.87	7.33	.3	.1	.89	.03	.04	0.0	0.0	327.0	3.0	0.0	71.0	6.0
15/11	260	7.47	11.24	.7	.41	2.41	.08	.07	.03	.01	493.0	3.0	2.0	99.0	20.0
	261	5.78	8.7	.42	.23	3.05	.02	.03	.02	0.0	427.0	1.0	1.0	82.0	4.0
	263	8.9	9.93	.18	.01	.86	.04	.04	0.0	0.0	605.0	2.0	1.0	105.0	3.0
15/12	265	7.04	9.19	.19	.02	.89	.04	.03	0.0	0.0	523.0	1.0	1.0	87.0	3.0
	266	30.39	28.87	.07	0.0	.41	.21	.01	0.0	0.0	366.0	0.0	0.0	96.0	0.0
	267	13.64	15.39	.12	0.0	.54	.1	.04	0.0	0.0	1,679	1.0	1.0	92.0	0.0
	268	13.41	13.79	.09	0.0	.45	.08	.03	0.0	0.0	1,516	1.0	1.0	107.0	0.0
15/13	394	2.68	8.74	.46	.25	5.16	.04	.04	.01	0.0	975.0	2.0	1.0	121.0	6.0
	395	20.48	23.63	.55	.33	3.32	.24	.06	.01	0.0	>2,000	3.0	2.0	162.0	0.0
	396	12.46	14.54	.24	.08	1.21	.09	.04	0.0	0.0	1,284	1.0	1.0	141.0	0.0
15/14	474	.86	11.4	.61	.39	5.1	.05	.07	.02	0.0	744.0	3.0	2.0	135.0	0.0
	475	16.81	18.06	.54	.34	3.27	.15	.06	.01	0.0	>2,000	3.0	2.0	148.0	0.0
	476	12.9	10.32	.25	.34	1.07	.08	.05	0.0	0.0	867.0	3.0	1.0	220.0	0.0
	477	24.62	31.9	.25	.07	1.31	.27	.05	.01	0.0	>2,000	2.0	1.0	151.0	0.0
15/15	397	16.6	20.89	.17	.04	1.46	.13	.04	0.0	0.0	>2,000	2.0	1.0	134.0	0.0
	399	28.97	32.53	.07	0.0	.3	.27	.02	0.0	0.0	>2,000	1.0	1.0	128.0	0.0
	398	16.65	19.83	.15	0.0	.92	.13	.05	0.0	0.0	>2,000	4.0	1.0	129.0	0.0
15/16	478	2.16	19.14	.54	.35	4.56	.06	.08	.01	0.0	448.0	3.0	2.0	127.0	0.0
	479	4.5	17.45	1.07	.85	14.86	.1	.15	.02	.01	4,400	7.0	4.0	150.0	3.0
	480	18.11	22.97	.86	.64	7.41	.25	.04	.01	0.0	>2,000	4.0	1.0	172.0	0.0
	481	30.0	30.8			.53					7,000				
	482	29.78	37.95	.25	.05		.32	0.0	0.0	0.0	>2,000	1.0	0.0	173.0	0.0
15/17	484	11.41	14.51	.27	.09		.1	.01	.01	0.0	1,386	1.0	0.0	126.0	1.0
	400	5.41	26.9			5.54									
	401	31.72	15.4			8.49									
	402	18.5	25.88	.14	0.0	.69	.14	0.0	0.0	0.0	>2,000	0.0	0.0	155.0	0.0
	403	9.83	10.44	.16	.02	.6	.05	.01	0.0	0.0	947.0	0.0	0.0	117.0	0.0
15/18	404	20.15	23.7	.2	.03	.78	.17	0.0	.01	0.0	>2,000	0.0	0.0	151.0	0.0
	406	2.48	23.17	.71	.43	5.19	.05	.03	.01	.01	>2,000	3.0	1.0	153.0	4.0
	407	20.94	28.22	.11	.0	.84	.2	.01	0.0	0.0	>2,000	0.0	0.0	169.0	0.0
	408	15.84	17.55	.16	.1	1.12	.12	.01	0.0	0.0	>2,000	1.0	0.0	173.0	0.0
	409	9.05	9.84	.1	0.0	.53	.05	0.0	0.0	0.0	814.0	0.0	0.0	101.0	0.0
15/19	486	3.09	23.03	.57	.39	2.8	.03	.03	.01	0.0	>2,000	2.0	1.0	141.0	0.0
	487	.98	28.47	.14	0.0	.66	.01	.01	0.0	0.0	>2,000	0.0	0.0	136.0	0.0
	489	2.13	23.16	.28	.1	1.46	.01	.04	0.0	0.0	1,388	2.0	1.0	113.0	0.0
15/22	414	21.57	27.86	.09	0.0	.54	.19	.03	0.0	0.0	>2,000	1.0	1.0	169.0	0.0
	410	7.2	17.88	1.26	.99	4.02	.1	.17	.03	.02	>2,000	8.0	4.0	171.0	17.0
	411	3.36	25.21	.68	.49	2.26	.03	.1	.01	.01	>2,000	4.0	2.0	156.0	0.0
	412	30.4	10.03			8.27					9,200				
	413	38.61	32.5			1.54					7,500				
15/24	17.038	21.92	20.0	.5	.28	4.9	.21	.09	.01	0.0	>2,000	4.0	2.0	152.0	0.0
	17.039	33.24	30.11	.2	.03	1.06	.28	.05	0.0	0.0	>2,000	2.0	1.0	152.0	0.0
	17.040	10.3	12.31	.12	0.0	.61	.05	.08	0.0	0.0	796.0	2.0	2.0	113.0	0.0
15/25	801	10.69	14.55	.28	.13	1.58	.07	.06	.01	0.0	1,292	2.0	2.0	113.0	0.0
	802	30.54	36.91	.07	0.0	.59	.28	.04	0.0	0.0	1,555	1.0	1.0	124.0	0.0
	803	10.75	11.07	.47	.33	1.51	.04	.1	.01	.01	315.0	3.0	2.0	118.0	15.0
	803<	15.75	17.47	.06	0.0	.32	.16	.04	0.0	0.0	1,150	1.0	1.0	109.0	0.0
15/26	17.042	20.41	20.14	.11	0.0	.72	.22	.03	0.0	0.0	>2,000	1.0	1.0	155.0	0.0
	17.043	20.96	24.38	.13	0.0	.57	.23	.03	0.0	0.0	>2,000	1.0	1.0	159.0	0.0
	17.044	29.35	34.12	.51	.34	2.09	.4	.08	0.0	0.0	>2,000	4.0	2.0	178.0	0.0
15/27	804	2.53	8.61	.41	.21	3.82	.03	.05	.01	0.0	406.0	2.0	1.0	138.0	7.0
	805	13.88	18.78	.28	.11	2.32	.14	.04	0.0	0.0	>2,000	1.0	1.0	150.0	0.0
	806	12.01	17.74	.19	.04	1.1	.12	.03	0.0	0.0	>2,000	2.0	1.0	139.0	3.0
	807	22.09	28.08	.16	0.0	.87	.23	.03	0.0	0.0	1,748	1.0	1.0	138.0	0.0
15/28	17.045	6.29	7.02	.32	.13	1.32	.04	.05	.01	0.0	414.0	1.0	1.0	123.0	6.0
	17.046	7.14	10.08	.14	0.0										

#### APPENDIX IV

#### Chemical Analysis of the Groundwater

## WATER ANALYSIS

Pit	CL	GMS/L					Sr	CL	SO4	X.S.S.W				Ca	Mg	Sr	Mg Cl	Mg K	Ca Cl	Mg Ca	W. T. Depth	Temp °C
		Na	K	Ca	Mg	Na				K	Ca	Mg										
Profile I - II																						
11/22	26.4	4.0	15.0	.6	.73	.16		1.33	1.43	1.36	1.46	1.72	.12				.01	.27	.03	.22	1.7	
11/23	108	6.25	59.0	2.02	1.24	4.9		5.44	2.24	5.35	4.93	2.93	3.71				.05	2.43	.01	3.95	1.0	
11/25	143	3.7	77.5	2.22	2.1	6.17		7.2	1.33	7.03	5.42	4.97	4.67				.04	2.78	.01	2.94	.9	
11/26	70.9	2.85	37	1.25	1.64	3.02		3.57	1.02	3.35	3.05	3.88	2.28				.04	2.42	.02	1.84	.9	
11/28	9.1	.85	5.3	.21	.37	.4		.45	.3	.48	.51	.87	.3				.04	1.9	.04	1.08	1.35	
13/3	10	3.0	5.7	.3	.76	.63		.5	1.07	.51	.73	1.8	.47				.08	2.1	.08	.83	1.3	
Profile III - IV																						
13/44	161	6.52	88.6	3.7	1.1	5.0	.025	8.11	2.35	8.04	9.05	2.62	3.79	3.25			.03	1.35	.01	4.55	0.72	
13/45	189	4.44	101.2	4.0	1.2	6.2	.025	9.5	1.6	9.18	9.78	2.86	4.7	3.25			.03	1.55	.01	5.17	0.37	
13/36	192	4.68	102.3	4.4	1.2	6.8	.022	9.68	1.68	9.28	10.76	2.86	5.15	2.86			.04	1.55	.01	5.67	0.3	
Profile V - VI																						
15/9	38.5	5.96	18.4	0.9	0.9	2.5	.022	1.94	2.14	1.67	2.2	2.14	1.89	2.86			.06	2.78	.02	2.78	0.56	
15/10	75.2	8.22	41.0	1.8	1.3	4.5	.03	3.79	2.96	3.72	4.4	3.1	3.41	3.9			.06	2.5	.02	3.46	0.58	
15/11	125	8.88	67.4	2.8	1.1	6.3	.028	6.3	3.19	6.11	6.85	2.62	4.77	3.64			.05	2.25	.01	5.73	0.7	
15/12	121	6.12	64.7	2.7	1.3	5.7	.034	6.1	2.2	5.87	6.6	3.1	4.32	4.42			.05	2.11	.01	4.38	1.0	
15/16	173	2.85	85.6	4.8	3.1	8.0	.067	8.7	1.03	7.77	11.74	7.38	6.06	8.7			.05	1.67	.02	2.58	0.62	
15/17	139	5.01	69.8	3.7	1.8	7.6	.042	7.0	1.8	6.33	9.05	4.29	5.76	5.45			.05	2.05	.01	4.22	0.48	
Profile VII - VIII																						
13/39	141	2.31	70.4	3.1	3.0	7.2	.072	7.11	.83	6.39	7.58	7.14	5.45	9.35			.05	2.32	.02	2.4	0.7	
13/40	188	2.24	92.0	5.4	3.0	10.4	.088	9.48	.81	8.35	13.2	7.14	7.88	11.43			.06	1.93	.02	3.47	0.52	
13/41	183	3.51	88.2	5.0	2.1	12.3	.039	9.22	1.26	8.0	12.22	5.0	9.32	5.06			.07	2.46	.01	5.86	0.85	
13/59	180	3.04	86.1	4.8	2.5	11.0	.054	9.07	1.09	7.81	11.74	5.95	8.33	7.01			.06	2.29	.01	4.4	1.0	
13/60	184	2.12	83.0	5.5	3.5	13.6	.071	9.27	.76	7.53	13.45	8.33	10.3	9.22			.07	3.89	.02	3.89	0.74	
13/62	185	3.48	92.6	5.8	1.8	9.4	.049	9.32	1.25	8.4	14.2	4.29	7.12	6.36			.05	1.62	.01	5.22	0.62	
13/63	147	5.64	74.4	4.5	1.5	7.0	.040	7.41	2.03	6.75	11.0	3.57	5.3	5.19			.05	1.56	.01	4.67	0.7	
13/70	108	6.12	56.2	3.0	1.6	5.5	.037	5.44	2.2	5.1	7.3	3.81	4.17	4.81			.05	1.83	.01	3.44	1.0	
13/72	191	4.04	102.5	3.7	1.4	5.6	.028	9.63	1.45	9.3	9.05	3.33	4.24	3.64			.03	1.51	.01	4.0	0.7	
13/75	190	4.54	105.9	3.5	1.2	3.1	.023	9.58	1.63	9.61	8.56	2.86	2.35	2.99			.02	.89	.01	2.58	0.63	
13/76	190	4.78	103.4	3.8	1.2	5.0	.023	9.58	1.72	9.38	9.29	2.86	3.79	2.99			.03	1.32	.01	4.17	0.5	
13/81	191	5.35	99.7	4.3	1.1	7.4	.022	9.63	1.92	9.05	10.51	2.62	5.61	2.86			.04	1.72	.01	6.73	0.17	
Profile IX - X																						
15/31	83.8	4.0	45.5	1.43	1.03	5.9		4.22	1.43	4.12	3.49	2.44	4.46				.07	4.13	.01	5.73	0.75	27
15/28	130	7.45	84.5	2.76	1.65	7.57		6.55	2.67	7.66	6.74	3.9	5.73				.06	2.74	.01	4.59	0.75	
15/24	53.5	10.9	28.0	1.13	1.42	2.55		2.7	3.92	2.54	2.76	3.36	1.93				.05	2.26	.03	1.8	0.75	25
15/6	13	1.45	7.0	.37	.67	.66		.65	.52	.63	.9	1.58	.5				.05	1.78	.05	.99	0.7	
15/5	9.3	1.9	4.8	.32	.76	.45		.46	.68	.43	.78	1.8	.34				.05	1.41	.08	.59	1.15	
15/4	70	6.4	35.5	1.64	1.85	5.65		3.52	2.3	3.22	4.0	4.38	4.28				.08	3.45	.03	3.05	0.42	
13/82	169	6.0	100	2.78	1.36	6.42		8.51	2.15	9.07	6.79	3.22	4.86				.04	2.31	.01	4.72	0.1	19.4
13/79	188	5.45	110	3.04	1.19	6.64		9.47	1.96	9.98	7.43	2.81	5.03				.04	2.18	.01	5.58	0.32	28
13/64	192	10.0	102	6.26	.72	11.5		9.67	3.59	9.25	15.3	1.71	8.71				.06	1.84	.01	15.97	0.3	27
13/50	186	3.95	115	2.32	1.46	4.61		9.37	1.42	10.43	5.67	3.45	3.49				.02	1.99	.01	3.15	0.4	
13/48	120	7.33	64	2.69	1.41	7.02		6.04	2.63	5.8	6.57	3.34	5.31				.06	2.61	.01	4.98	0.75	
Scattered Pits in the Sabkha.																						
13/27	33.1	2.83	18.2	.67	.86	1.82		1.67	1.02	1.65	1.68	2.04	1.38				.05	2.72	.03	2.12	.85	24
13/42	27.6	1.36	15.2	.6	.99	1.37		1.39	.49	1.38	1.46	2.36	1.04				.05	2.28	.04	1.38	.85	22
13/16	62.4	4.89	34.1	1.28	.96	3.36		3.15	1.76	3.55	3.12	2.29	2.55				.05	2.63	.02	3.5	1.1	22