PALAEOENVIRONMENT STUDIES IN THE MIOCENE (LIBYA, AUSTRALIA)

BY

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A thesis submitted for the degree of Doctor of Philosophy
of the University of London.

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GENERAL INTRODUCTION AND TABLE OF CONTENTS :

This project comprises two parts. The first deals with Miocene rocks in Libya and was originally the subject of the entire thesis. However, after a month of field work in Libya the author's visa was not renewed and he had to return home. Not knowing whether it was going to possible to return, an alternative subject was arranged. As the author was scheduled for two holidays in Australia in the following two years, it was decided to combine business with pleasure and study the Miocene in Victoria. As it transpired, it became possible to return to Libya and so both projects have been studied. The Libyan area is described in Volume 1, the Victorian area in Volume 2.

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ABSTRACT

The environments of deposition and geological history of lower and middle Miocene rocks belonging to the Marada group have been considered. The rocks, cropping out in east-west trending escarpments in the area of the Zelten oilfield in central Cyrenaica, Libya, are flat lying and consist of rapid alternations of various lithological types.

The basis of the study has been a detailed examination of the fossils and bioturbation from an ecological point of view. The fossils have been grouped into biofacies, 20 of which have been recognised, while the bioturbation has been both described and grouped into 10 ichnofacies. The environments represented by the rocks have been deduced from their internal structures and fossil content.

Two phases of deposition have been recognised:

(i) An earlier clastic phase, comprising fluviatile sands and shales together with intertidal and subtidal calcareous sands, shales and interlaminated beds, found in the lower parts of the southern and western sections. The fluviatile sediments contain a rich biota of vertebrates and silicified wood indicating a tropical savannah climate, while the intertidal sediments are characterised by heavy bioturbation by Ophiomorpha Lundgren and Caegichnus nom.nov. amongst others. This phase is thought to be late Aquitanian and early Burdigalian.

(ii) A later phase of carbonate deposition, thought to be Burdigalian and Helvetian characterises the upper parts of the northern and eastern sections. It comprises richly fossiliferous shallow water limestones and estuarine calcareous sandstones and shales. The former were deposited in water depths of 0 - 50 metres and were nearly always affected by influxes of brackish water, only rarely being wholly characterised by fully marine genera such as Echinolampas, Idmonea and Lopha. In most units

large numbers of euryhaline genera like Crassostrea and Placenta are present, and they also characterise the estuarine calcareous sands and shales.

CHAPTER I

INTRODUCTION

Geographic Setting (figure I.1., enclosure 1)

The area considered covers 11,050 sq. kms of central Cyrenaica, Libya. The ancient oasis of Marada (19° 15'x 29° 10') is located in the north western part, and the much newer oil oases of Raguba, Zelten and Waha occur at the other three corners respectively. The northern part including both Raguba and Zelten comprises part of Esso concession 6, while the southern part around Waha is in oasis concession 59.

The Oligocene and Miocene rocks of the area, undisturbed and seemingly completely flat lying are exposed in more or less east west elongate scarps. The outcrop of the Oligocene follows a northwest-southeast trend from Dahra to Raguba, but then swings away southwards towards Beda. The Miocene escarpment, 15 kms to the northwest, follows the Oligocene as far as Raguba, but then swings away eastwards to form the Dor Marada - Dor Zaggut. This retreat of the scarp is, however, due to erosion oblique to the escarpment, for the southeastward trend is continued in a large outlying feature over 100 kms long joined in the northeast to the Dor Zaggut - the Jebel Zelten. A number of isolated hills or jebels occur between the Dor Zaggut and the Jebel Zelten, clustered around Marada, Raguba and Zelten.

The top of the scarp, like much of the desert in the northern Sahara is covered by a flat very gently undulating gravel plain, the sarir. The escarpment of the Miocene is up to 150 metres high, but is usually about 100 metres. Softer beds, typical of the southern parts of the area, are often covered by talus slopes, but generally the exposure is magnificent. At the bases of the escarpment, a narrow band

LIBYA

MEDITERRANEAN SEA

TUNISIA

ALGERIA

NIGER

TCHAD

U.A.R.

Tripoli

Sirte

Benghazi

Cyrene

Tobruk

Marsa el Brega

Agedabia

Giarabub

Aguila

Marada

Raguba

Zelten

Waha

Sebha

TRIPOLITANIA

SIRTE BASIN

GREAT SAND SEA OF CALANSCIO

CYRENAICA

CALANSCIO PLAIN

UBARI SAND SEA

FEZZAN

MURZUQ SAND SEA

TIBESTI PLAIN

Al Kufrah

0 100 kilometres

20 0 20 40 60 miles

SAND SEA

SCARPS

3 - 4 kms wide typified by wadis and washout channels occurs. At its base the watertable often comes close to the surface and, especially at the base of the Dor Marada - Dor Zaggut a salt marsh or sabkha is developed. It is often rich in vegatation, especially palm trees, and it is here that the Oasis is Marada is sited. The floor of the .desert is covered with thick sands, forming the sand desert. It scarcely ever moves, having a firm lag of coarse grains at the surface. Scattered over its surface are the dunes of the sand sea. Large dunes occur in the Ramlet Zaggut, Ramlet el Rachmat and south of Waha.

There is a gentle increase in topographic height southwestwards. The top of the Dor Zaggut escarpment for instance is between 179 and 189 metres above sea level, while on the southern side of the Jebel Zelten it is between 260 and 288 metres above sea level. This represents an inclination of about 1: 700 or a northward dip of approximately 6'. Thus though no such dip is evident in the sediments it must be present if the sections in the north are equivalent to those in the south.

Previous work in the area and object of project.

Until recently, the only published geological account on the Marada area was that of Desio (1935). The scientific expedition to Al Kufra had passed through the area in 1931, and Desio designated the limestones of the escarpment the Marada formation. In the report of the expedition Desio published faunal and floral lists for the area. He measured a section 80 metres thick at Garet el Mazzala, northwest of Marada, and recorded a large number of species both there and on the road up the scarp on the way to Agheila (directly to the northwest). He noted that at the bottoms of Garet el Gehennah and Garet el Luban, Nummulitic Oligocene was present. From his studies in the Marada area he suggested that the rocks were laid down along an ancient shore line near a delta which more or less ponded a lagoon (represented by gypsiferou

green and polychromatic shales). The basal beds of the Garet el Mazzala section were, he concluded, Aquitanian, while both the Langianian and the Helvetian were represented higher up. He marked the whole of the area represented by the Zaggut and Zelten sections as Langianian - Helvetian, but considered that the sediments exposed upon the south side of the Jebel Zelten were Aquitanian. Upper Miocene sediments were not recognised in the area.

Descriptions of the Miocene fossils of Cyrenaica were given by Desio and his associates in the results of the Scientific Mission to the Oasis of Giarabub (northeast of Marada, on the Egyptian border) in 1929. Desio described the molluscs, echinoids and arthropods, Chiarugi described the petrified wood, Cippola described the bryozoans and Zuffardi Commercei described the corals.

A number of other authors have published faunal lists and descrip - tions of fossils from various localities in Cyrenaica but systematic collections have not been made from the Marada area since.

Colley (1963) summarised the regional geological setting of Libya. The Marada area lies within a wedge of southward-thinning Mesozoic and Tertiary sediments mantling the basement of the Sahara Shield. Miocene sediments in Cyrenaica are divisible into two elements:-

(i) The Cyrenaica platform, characterised by shelf limestones, sandy limestones and marls.

(ii) The Sirte basin, characterised by a rapid landward transi - tion from basinal shales into a mixed carbonate and clastic fluvio-marine facies. The Marada group belongs to this latter category.

In 1959 Professor Gill of Imperial College examined the area and instigated a research project. Selley (1968) began this with a sedi - mentologic survey of the Marada - Zelten area. As a result of his studies he recognised a number of environments largely confined to east-west trending belts. Owing to marked interdigitation of the rock types,

representing different environments of deposition, or facies, it was not possible to limit particular parts of the area to one such facies. Their zones of influence were defined though, and from north to south they comprise;

(i) Detrital limestone facies: these were deposited on offshore bars and barrier beaches, and are dominant in the northern part of the area.

(ii) Laminated shale facies: these were deposited in lagoons.

(iii) Shale, silt and sand facies: these were interpreted as intertidal sand and mud flats.

(iv) Sand, silt and shale facies: these were interpreted as being fluviatile. They predominate in the southern part of the area.

(v) Calcareous sandstone and sandy limestone facies: these beds are restricted to two north - south elongate belts and represent the deposits of estuarine channels.

This general lithostratigraphic framework is similar to the one described by Said (1962) from the Mogra formation of Egypt (the eastward equivalents of the Marada group).

The present author continued the project with the object of examining the abundant fossils from an environmental point of view and comparing the results with those of Dr. Selley. A comprehensive sedimentological and palaeontological picture having been built up, it was hoped that a clear and concise account of the history of the area during the Miocene would emerge. The project also provided a means of comparing the relative merits of sedimentology and palaeontology as tools for detailed environmental analysis.

Accordingly the project was started in 1965, but was interrupted by the difficulties outlined in the general introduction. In the restricted time available it was decided to range over as wide an area as possible and not to try and cover the area systematically. As

far as possible sections were examined as close as possible to those of Selley, but due to the nature of the terrain and the lack of detailed maps it was often not possible to identify ones' position relative to them exactly.

Sections were measured by tape, and by abney level where not corresponding to those of Selley. Each was divided up into a number of units, and the lithological and palaeontological characters noted. The term unit is taken throughout to denote the smallest division of rock encountered that was with ease differentiated in the field from above and below. Units were usually approximately a metre or a metre and a half thick. The analytical techniques employed in the laboratory have been considered at the beginning of each chapter, and so are not included here.

For the purposes of describing distributions the sections have been divided into five groups. (enclosures 2,3)

(i) The Marada sections: These sections in the west, around Marada (numbers 1,2,3,4)

(ii) The Raguba sections: These sections are clustered in jebels around Raguba (19,20,21,22,23,24)

(iii) The Zaggut sections: Those sections on the northern es - carpment (numbers 5,6,7,8).

(iv) The Zelten sections: Sections in the jebels around Zelten (numbers 9,10,11,12,13,14,15,16,17,18)

(v) The Northern Jebel Zelten sections: Those on the north side of the Jebel Zelten (25,26,27,28).

(vi) The Southern Jebel Zelten sections: Those on the south side of the Jebel Zelten (29,30,31,32,33,34,35,36,37,38,39).

The chapters are arranged as follows:-

Chapter 2 consists of an analysis of the fossils from an environ - mental point of view. From a consideration of the faunal lists for each

of the units, a series of biofacies were recognised. A discussion of these, with the environments they are thought to represent is given in Chapter 3.

At the inception of the project it was decided to undertake systematic study of the burrows to find out whether they could be of any assistance in environmental reconstruction. There follows chapter 4 therefore, in which the bioturbation is described and interpreted. In chapter 5 the structures have been grouped, much as have the fossils, into ichnofacies and the environment represented has been discussed.

There follows a chapter (6) in which the sediments are described and, together with the evidence outlined in the previous chapters, interpreted in terms of environments.

Chapter 7 is devoted to an account of the geological history of the area, deduced from an examination of the sections and the accumulated evidence of chapters 2 to 6.

During the process of the study many of the conclusions of Selley (1968 in press) were confirmed. Many of the features however, were interpreted differently. The interpretations of Selley are placed in parenthesis or discussed where appropriate. Though both Selley (1968 in press) and Desio (1935) had regarded the rocks as belonging to a formation, they fall much more naturally into a group (see the Report of the Stratigraphical code Sub-committee 1967).

Acknowledgements

The author wishes to express his deepest thanks to all those who have helped in making this project possible and in seeing it to its execution.

A N.E.R.C. Research Studentship from 1965 to 1968 and a grant in aid of field work from the Royal Society are gratefully acknowledged.

To Dr. D.V. Ager, who supervised the project, gave constant encouragement both in the field and in college and critically examined the manuscript under trying circumstances, I owe especial thanks. I am also very grateful to Professor Gill, who instigated the project and Dick Selley, who introduced me to the desert, the rocks and the problems involved, and with whom I had numerous discussions.

The project would of course, never have been possible without the aid of the oil companies in the desert, and it is with great pleasure that I recall the help, encouragement and hospitality I received at their hands. I should like to thank particularly Mr. B.B. Colley, Mr. C. Squyres and Mr. R. Wermeyer and many other members of the Oasis Oil Company, and Mr. J. Zhender of B.P. who loaned me a Landrover and driver (Mahmoud). I shall remember for a very long time the hospitality and great encouragement of Dr. R.W. Phillips and Dr. L. Smith of Esso Standard Libya, and the members of the Esso Seismic crew near Zelten who made every effort to make my stay there immensely enjoyable.

I have benefited enormously from discussions with Dr. R. Savage and John Harris of Bristol University, who are also working in the Zelten area, and with members of the Sedimentology department at Imperial College, especially Mr. D.J. Shearmen, Dr. G. Evans, Peter Bush and Derek South. My thanks are also due to Dr. G. Evans and Derek South for introducing me to the Recent tidal flats of the Norfolk and Lincolnshire coasts.

During the closing stages of the draughting of the thesis Mary Pugh gave an incalculable amount of help in her characteristically generous and whole-hearted fashion. Without her help at a critical stage I should probably not have been able to finish for a further month. Mrs. Sheila King, who typed the thesis, is also especially thanked. She not only typed it both quickly and efficiently, but also had to contend with a particularly trying hand-written script.

CHAPTER 2

THE FOSSILS

The abundance of specimens in the large number of units examined made it desirable to divide the fossils into a number of easily recog - nisable groups, generally sharing the same ecology. The groups so chosen were usually limited to one particularly recognisable species as in the case of Crassostrea gryphoides, or consisted of a number of closely related species characterised by a broadly similar form (normally a genus). In some instances the grouping cut across family boundaries, for example, boring bivalves were grouped together. The less common or rare species are listed without detailed description.

The descriptions of the groups - arranged as nearly as possible systematically, consists of a list of species where applicable (living species have been indicated by an asterisk), a general account of their occurrence and preservation, and a summary of their distribution, Detailed systematic work on the fossils did not come within the scope of the project, so no symonymies are included. The identification of these species recognised only by thin section examination has not been attempted because of the large number of units. The distribution of the groups has been defined both geographically and stratigraphically. Geographical dis - tribution has been indicated drawing contoured maps based on the percentage of units in each section in which each group occurs. Vertical distri - butions in the sections are largely concerned with the location of co - relation bands and the delineation of zones of influence of the important species. The distribution maps show up four major groups of fossils:

1. These that die out southwards (the completely marine fossils).

2. Those that die out southwards and northwards (the very shallow water and intertidal fossils).

3. Those that die out northwards (the continental fossils).

4. Those that die out eastwards and westwards (the brackish water estuarine fossils).

There follows a paragraph in which their ecology or presumed ecology is summarised. Information has been obtained from a wide variety of sources, the basic philosophy being that the ecology of the nearest living relative or failing that, the ecology of the genus or family as a whole is representative of the ecology of the fossil.

It is impressive how closely the distribution of the fossils is consistent with their extrapolated ecology, whether the data is specific, generic, or familial. The modes of occurrence and distribution of Crassostrea virginica for example seem to closely follow those of the fossil species Crassostrea gryphoides. The distribution of the two groups of the family Pectinidae (figure 2.16) show that Chlamys, at the present day having representatives that are euryhaline, is much more widespread than Pecten and Flabellipecten, of which all the living species are stenohaline. The same feature may be seen in the distribution of the groups of the suborder Scutellina; the Astriclypeidae having euryhaline living representatives and the Scutellidae not, (see figure 2.17). The close association of species and groups of similar extrapolated ecology is marked.

Because the area under consideration is Mediterranean, supplementary data has been added from ecologic work in the present Mediterranean sea.

The detailed description of the marine mollusc assemblages of the Rhone Delta by Van Straaten 1960, and the Manuel de bionomie benthique de la mer Mediterranee (Peres and Picard 1958) have been used. The terms Littoral, Infralittoral, Circalittoral and Sublittoral are only used when reference is made to the Mediterranean. In all other cases the terms intertidal and subtidal have been used to define the distribution of nearshore marine species.

Tables showing the number of units in which each group occurs and their occurrence and preservation expressed as percentages are listed in the following way:

1. The number of units in which the group occurs.
2. The percentage occurrence of that group in the various sediment types.
   - (i) limestones.
   - (ii) shales associated with limestones.
   - (iii) sandy limestones.
   - (iv) calcareous sands
   - (v) shales associated with calcareous sands
   - (vi) interlaminated sands and shales.
   - (vii) unconsolidated sands.
   - (viii) shales associated with unconsolidated sands.
3. The frequency of occurrence within a unit, which may be

   Rare (R):- the group is represented by one or two specimens only.

   Common (C):- the group is common.

   Abundant(A):- restricted to groups that crowd the bedding.

These are also expressed as a percentage of the total occurrence.

4. The types of preservation have been divided thus:-
   - (a) unbroken and unworn.
   - (b) broken only.
   - (c) worn only.

(d) broken and worn.

(e) fragmented (generally less than 0.25 the size of the original skeleton.

(f) those presumed to be in life position.

These also have been expressed as a percentage of the total occurrence: groups that have more than one preservation type in one unit will therefore total more than 100%. Where the preservation does not fall into any of these classes (as in the case of borings), no information has been given.

5. The average size of complete specimens in centimetres.

Further lists showing the percentage association of species with each other grouped into classes of 10% follow, and have been used to define the ecology of species for which there is little information from Recent relations. Associations of less than 50% have not been included.

GROUPS	nº of units	% occurrence in sediments								abundant			% types of preservation						size of complete specimens	% association with other groups					
		limestone		calcareous			sandy	uncons.		common		rare													
		lst	shale	snd	sh	inter	lstone	snd	sh				a	b	c	d	e	f		over 90	80-90	70-80	60-70	50-60	40-50
Crusteous calcareous algae	26	88		4		7				19	54	27	11	29			60	10	5 cm						
Spherical calcareous algae	102	88	7	3	3	1				5	46	51	27	13			60	25	5						
Dicotyledenous wood	28	4					25	64	4	60	30	9	20	53			37		800						
Palm wood	10						30	70		70	30		20	10			70		300						
Leaves	7								100	43	28	28	100						5						
Monastrea ellisiana	16	62		19	6	6	6			68	32		35	65					10						
Cliona and Polydora borings	24	77				14	4																		
Calcareous worms	5	100								100				100											
Balanus concavus	43	63		25			16			63	37		87	13				15	3						
Decapoda	65	51		15	3	15	17			51	49			100											
Gibbula aquitanica	14	48		7	7		38			64	36														
Turreted gastropods (a)	145	55		21	5	4	14			17	59	22	23	24	6	12	34								
(b)	10	60		20			20			50	50														
Vermetus sp	25	96					4			44	44	12													
Strombus bonellii praecedens	8	63				12	25			88	12		63	38					5						
Cypraea subovum	21	80		5		5	10			91	9		34	46	4	13			9						
Natica spp.	11	73		9	9		9			73	27		54	27	18				3						
Conus spp.	21	76	5	5		5	9			62	38		49	43			8		4						
Buliminus sp.	10	30		10	20	20	20			70	30		80	20					1						
Crassostrea gryphoides	195	61	3	15	7	8	9			24	48	25	17	13	6	17	70	5							
Lopha plicatula	101	86	4	7	4	1				30	50	20	27	24	8	16	60	4	7						
Ostrea edulis group	38	79	5	11	2	3				65	32	3	29	13	9	16	34		5 - 10						
Ostrea frondosa subfimbriata	29	79	3	11	7					46	51	3	53	12		23	12		4						
Chlamys spp	214	70	4	10	5	4	7			42	53	3	20	16		40	52								
Pecten and Flabellipecten	99	84	4	6	3	3				54	43	3	23	13		23	36								
Spondylus crassicosta.	31	84	10	7						94	3	3	16	19	6		32	13	10						
Anomia ephippium r-striata	16	50	12	38						38	62		75	14			11		2						
Placento miocenico	57	72	5	12	2	9				11	56	33	30	39		5	28		12						
Ribbed bivalves	55	56		20	2	5	16			27	67	6	24	25	14	22	14								
Capsa lacunosa	31	48		23	3	6	19			26	68	6	55			42			3 - 6						
Corbula basteroti	25	32	4	16		12	36			36	24	40	70	18			8		1 - 2						
Boring bivalves	42	38	2	33		10	14			40	57	3													
Smooth bivalves	164	60	2	15	7	6	10			15	59	25	34	20		7	39								
Idmonea spp.	12	54	23	8	8	8				15	69	15		100					1						
Trigonopora moniliferum	290	74	7	8	2	2	4			14	41	45	5	53		1	41		15						
Holoporella desioi	186	80	3	7	4	2	2			14	61	25	9	50	2	4	35		10						
Retepora cellulosa	7	100								86	14			60			40		2						
Asteroid plates	48	79	4	10	2	2	2			79	21		100						1						
Regular echinoids	9	78		11	11					100			44	55											
Scutellids without lunules	26	100								42	46	12	29	23		14	32		10						
Scutellids with lunules	57	58		16	2	5	19			46	47	7	17	23		23	37		4 - 7						
Echinolampas spp.	27	92	4	4						18	67	15	42	22		11	25		12						
Agassizia cyrenaica	9	100								44	56		70	30					3						
Spatangoids	36	78	3	5	3	8	3			75	25		6	37		3	54								
Teeth	14	36		29	7	7	21			57	43		100												
Bone	50	16	2	20	2	10	26	22	2	58	42		12	12		76									

General distributions of the groups.

(i) Those that die out southwards.

Crusteous calcareous algae, Spherical calcareous algae, Monastraea ellisiana, Cypraea subovum, Conus spp., Lopha plicatula, Ostrea edulis group, Ostrea frondosa subfimbriata, Pecten and Flabellipecten, Spondylus crassicosta, Smooth bivalves, Idmonea spp., Trigonopora moniliferum, Retepora cellulosa, Scutellids without lunules, Echinolampas spp., Agassizia cyrenaica, Asteroid plates.

(ii) Those that die out southwards and northwards.

Balanus concavus, Decapoda, Turreted gastropods (a), Vermetus sp., Strombus bonellii praecedens, Buliminus sp., Crassostrea gryphoides Chlamys spp., Anomia ephippium ruguloso-striata, Placenta miocenica Ribbed bivalves, Corbula basteroti, Boring bivalves, Holoporella desioi Regular echinoids, Scutellids with lunules, Spatangoids, Teeth,

(iii) Those that die out northwards.

Dicotyledenous wood, Palm wood, Leaves, Bone.

(iv) Those that die out eastwards and westwards.

Balanus concavus, Turreted gastropods (b), Strombus bonellii praecedens, Natica spp., Buliminus sp,, Gibbula aquitanica, Capsa lacunosa, Corbula basteroti, Scutellids with lunules, Teeth.

PLANTS

Calcareous algae

The Miocene calcareous algae of Cyrenaica were described by Raineri (1923), who recognized eight species of rhodophytes.

Archaeolithothamnium intermedium, Raineri

A. cyrenaicum, Raineri.

Lithothamnium ramoisissimum, Reuss

Lithophyllum lichenoides, Ellis and Solander.

L. expansum, Phil.

L. lemoini, Raineri.

L. (dermolithon) cremae, Raineri.

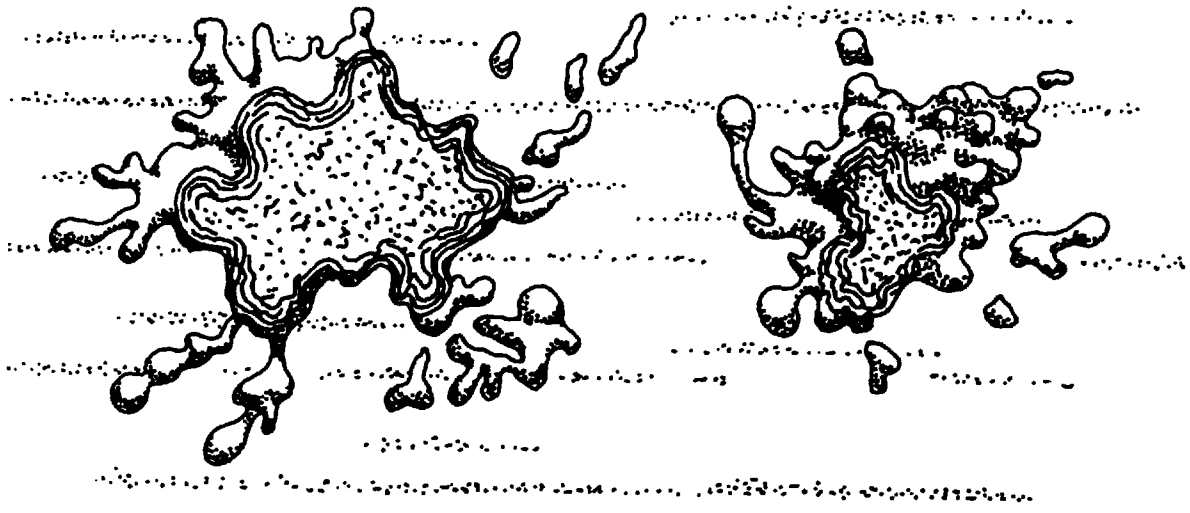
Melobesia sp.

The specific identification of these forms is impossible without sectioning and this has not been attempted. Two forms are recognised:

(a) Crusteous forms

Mode of Occurrence: Crusteous calcareous algae are common but usually fragmented. They occur in 26 units, nearly always limestones. Occasionally, larger horizontally-disposed masses up to 5 cms long, partly spherical but typically crusteous occur, and may form a ramifying horizontal and inclined plexus through the sediment (section 7). In sections 17 and 18 these are intimately associated with vermiform gastropods. Masses 4 cm in diameter are distributed through the bed encrusting shell debris or surrounding sediment-filled hollow cavities, evidently the remains of soft sponges or algae (figure 2.3c).

Geographic Distribution: Crusteous calcareous algae occur throughout the Zaggut and Zelten sections and at Jebel Auf.



a Spherical calcareous algae with radial protuberances (x1)

Section 5



b Ironstone rings around in situ dicotyledenous and palm roots. Note the alignment and the traces of foresets on the rings. (The hammer is 40cm long)

Section 20

Figure 2.1

Ecology: Living crusteous calcareous algae are most abundant in fully saline sea water at depths of 30-60 metres, where there is below 50% luminosity and the water is calm. In the Mediterranean they occur on consolidated sands and calcareous sands in the subcoralline facies of the Circalittoral (Senes 1967).

(b) Spherical Forms

Mode of Occurrence: These occur commonly and abundantly in 102 limestone units, usually as 0.3 - 0.6 cm fragments, but also as slightly broken or complete spheres with well developed irregular radial protuberances. In many units in the Zelten and Zaggut sections complete specimens are evenly distributed through the sediment, and not in contact with one another. As no joining protuberances are ever found, they must be independent and free living individuals. Their even distribution suggests they are in or near life position. The core around which the skeleton was precipitated is usually a shell fragment or a lime mud pellet (figure 2.1a)

Geographic Distribution: Spherical forms are present throughout the Zaggut and Zelten sections with a maximum in the former. They are also present at the tops of the Marada sections (figure 2.15a).

Ecology: Living spherical forms are free living; Lithophyllum racemus which has much the same form, washes around on the open sea floor of the Mediterranean in calm waters of rather low energy. Very shallow waters are not colonised in large numbers, as luminosity of more than 70% is not tolerated, typical depths being 15 - 30 metres (rarely down to 80 metres). It occurs in the hard subcoralline facies of the Mediterranean Circalittoral.

Silicified Wood

Silicified wood was reported by Chiarugi (1929) from Giarabub. He listed:

Palmoxylon aschersoni, Schenk.

P. giarabubense, Chiarugi.

P. libycum, Krausel.

Nicolia aegyptiaca, Unger

N. giarabubense, Chiarugi.

Laurinoxylon desioi, Chiarugi.

In the report of the Cufra expedition, Desio (1935) gave a floral list for the Marada area (Guerat-el-Heira and the Jebel Zelten):

Dicotyledons: Sterculioxylon fezzanensis

Nicolia giarabubensis, Chiarugi.

Evodioxylon oweni, Chiarugi.

Palms: Palmoxylon sp.

As with the calcareous algae, detailed identification of the wood requires thin sectioning, and this has not been attempted. Two broad groups are recognised by their overall structure.

(a) Dicotyledenous Wood

Mode of Occurrence: This is found in 28 units, mainly sands and calcareous sandstones, in the form of silicified trunks and angular splinters, often strongly ferruginised (40%). A few fragments are lignitic. The large trunks are weathered out of the soft sand as the scarp retreats and remain as a lag at lower levels in the sections. Only in two localities were trunks seen partially within the sediment. At section 19 a trunk over 2 metres long and 0.3 metres diameter is oriented with its long axis 313° NW, and near the base of section 2, thirteen such trunks lying beside each other on one bedding plane 22 metres wide are oriented in an arc between 335° and 50°. The base of the largest specimen, one metre in diameter and over 8 metres long, points southward. The trunks were there - fore laid down by a dominantly SSW-NNE flowing current.

Distribution: Dicotyledenous wood is commonest in the sands at and near the bases of the Marada and southern Jebel Zelten sections. It is rarer to the north, where scattered fragments occur in calcareous sandstones.

(b) Palm Wood

Mode of Occurrence: This occurs in 10 units, closely associated with dicotyledenous wood. At the base of section 20, vertically disposed tubular rings of ironstone are exposed on a horizontal surface of sand. The bulk have swollen portions similar to the swollen bases of palm trees, but a few have moulds of dicotyledenous wood on their insides, and many are too irregular to be either. The ironstone is constantly 0.3 - 0.5 cm thick, and the diameter of the central hole 2.5 - 10 cm, rising to 20 cm in the swellings. Clumps of rings covering an area of 4 sq. metres occur every three metres or so, and all are inclined 10° - 35° from the vertical in an arc 205° - 230° southwest (in the same direction as the foresets of the festoon bedding) (figure 2.1b).

Geographic Distribution: Silicified wood is exclusive to the basal sands of the sections on the south side of the Jebel Zelten, and at Jebel Raguba (20).

Ecology: Palm trees are continental, occurring dominantly in the tropics. Principi (1932) concluded that the Miocene climate indicated by the fossil trees was rather more tropical than it is now, and Desio (1935) quoted Chiarugi's comment that the climate indicated was "Pleasant i.e. uniformly hot and humid, but with periods of relative drought, the characteristic climate of the Savannah".

Leaf Impressions

Mode of Occurrence: Leaf impressions have been found in 7 units, as rare but well preserved transparent shiny impressions of unveined and occasionally veined leaves and striated rushes (figure 2.2a).

Geographic Distribution: They are exclusive to the shales at the bases of the sections on the south side of the Zelten. Most of the specimens were collected from an outcrop in the washout 7½ Km west of section 30, associated with Hydrobia sp.

Ecology: Myrica integerrima (the Bog-myrtle) a tropical marshy plant has been identified by D. Ferguson of the Institut voor Systematische Plantkunde, Utrecht.

ANTHOZOA

Monastraea ellisiana (Defrance)

Mode of Occurrence: M. ellisiana occurs in 16 limestone and calcareous sand units as rare and isolated decalcified individuals, usually the right way up but never certainly in position. It is associated with a hard bottom marine fauna.

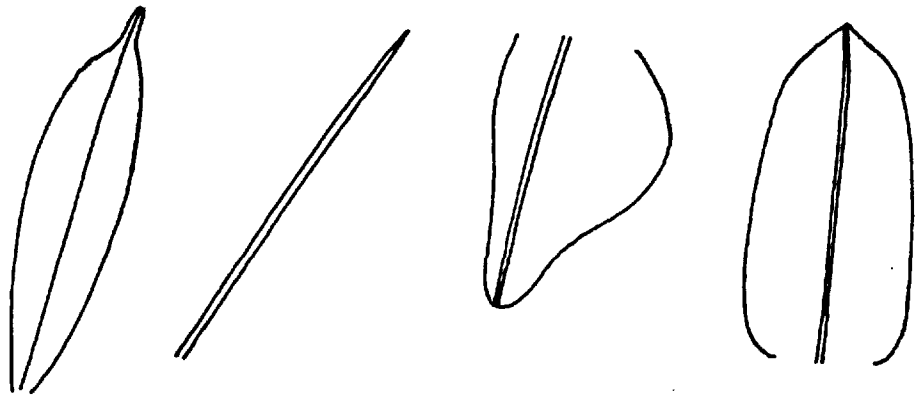
Geographic Distribution: It is present in the northern sections, gradually dying out southwestwards. It occurs at the top of the Marada, the base of the Zelten and throughout the Zaggut sections.

Ecology: Living species of Monastrea indicate normal salinity, non-depositional areas with strong light and a water temperature of over 18°C. They occur on the seaward slopes of reefs away from the highest energies in depths shallower than 20 metres.

Cliona and Polydora Borings

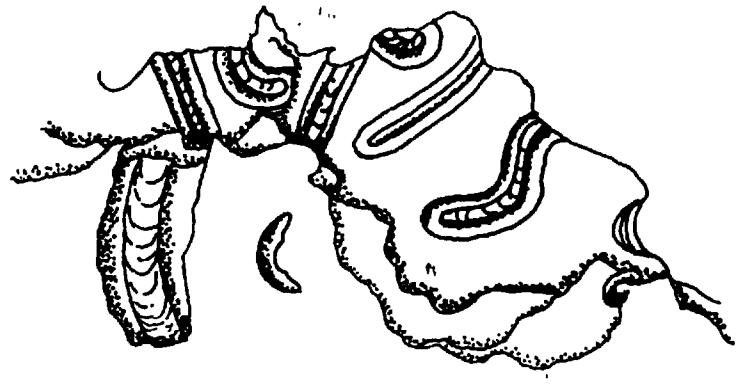
Mode of Occurrence: Bored shells and Cobbles occur in 24 limestone and interlaminated sand and shale units. The hosts of the borings are:

Crassostrea gryphoides	40.9%
Ostrea plicatula	36.4%
Cobbles and Pebbles	18.2%
Placenta miocenica	4.5%



a Leaf impressions (x1)

Outwash 7·5km west of section 30



b Fragment of Crassostrea gryphoides Schlotheim infested with Polydora ciliata Johnston. (x4)

·Section 17



(i) (ii) (iii)

c Decapoda

(i) crab carapace (x3) Section 10

(ii) elongate sculptured Callianassa chela (x1) Section 34

(iii) short smooth Callianassa chela (x1) Section 4

Figure 2.2

Horizontal and low angled curved U-shaped tubes with spreiten, typical of * Polydora ciliata (Johnston, see Boekschoten 1966) and * P. hoplura (Clap, see Lessertisseur 1955) occur in Crassostrea gryphoides shells (figure 2.2b), while infestations of round pores connecting beneath the shell surface - characteristic of * Cliona megastoma, Fisher, form a pentagonal pattern (photo 2.1a) or a close knit plexus. The latter leads to a spongy shell in Ostrea plicatula and O. fimbriata (photo 2.1b). The surfaces of some clay pebbles are covered with shallow elliptical or oval, randomly oriented borings 0.2 cm long x 0.1 cm wide, and 0.1 cm deep, the larger ones meandering and showing a central ridge. These are also produced by Cliona.

Geographic Distribution: Bored shells and Cobbles are present in the lower parts of the Zelten and Zaggut sections and at Garet-el-Cra.

Ecology: Polydora ciliata is a very common sublittoral worm, occuring especially in areas between low tide and 20 metres where the salinity is reduced. Cliona megastoma attacks shells and pebbles in fully marine waters between 0 and 200 metres in areas of non-deposition.

Calcareous Worm Tubes

Mode of Occurrence:

Rare specimens occur in 5 limestone units associated with Crassostrea and smooth bivalves.

Geographic Distribution: They are mainly concentrated towards the bottom of the Zelten sections.

Ecology: Calcareous worms encrust shells and stones throughout the world and at all depths of water.



Photo. 2.1a. Placenta micenica with borings of Cliona megastoma ramifying through the shell.(x3) Section 11



Photo 2.1b. Ostrea fimbriata with borings of Cliona megastoma. Section 5

ARTHROPODA

Crustacea

Balanus concavus Bronn,

Mode of Occurrence: This barnacle is found associated with a wide variety of stenohaline and euryhaline species in limestone, calcareous sand and calcareous sandstone units. It is usually rare, but scattered well preserved individuals are found within the sediment, or encrusting bivalves, especially Crassostrea gryphoides (when it reaches 3.0 cm x 2.6 cm size). In fine-grained limestones, in which the shells are decalcified, moulds of small (0.4 x 0.3 cm) Balanus concavus encrust the insides of smooth bivalves.

Geographic Distribution: B. concavus occurs in the calcareous sandstones of the Marada and Jebel Zelten sections and throughout the Zelten and Zaggut sections.

Ecology: Species of Balanus are best developed at the present day in wave-exposed localities, though they are also found in areas of high current activity subtidally. They can tolerate marked variations in the salinity.

Decapoda

Mode of Occurrence: These almost exclusively occur as isolated poorly preserved chela scattered through 65 units and associated with a variable fauna. They are best preserved in the limestones and calcareous sandstones, but are very fragile in other sediments. Two types are recog - nisable:- coarsely sculptured elongate chela (figure 2.2c(ii)), and smoother shorter forms (figure 2.2c(iii)). Both are referable to Callianassa, the former (occurring dominantly in calcareous sandstones and calcareous sands and clays) approaches C. menziesi Withers, from the West Indian

Miocene, while the latter (occurring mainly in limestones) is close to C. matsoni Rathbun, from the Tertiary of the Gulf Coastal Plain. A few poorly preserved circular crab carapaces with 3 parallel rows of irregular prominences were also found (figure 2.2c(i)).

Geographic Distribution: They occur rather randomly throughout the area, but reach a maximum near Zelten. They are present throughout the Marada sections, towards the bottoms of the Zaggut sections and southwards to the calcareous sandstones of the Jebel Zelten.

Ecology: Callianassa is an extremely widespread deep burrower in shallow marine water at the present day. For instance, Callianassa major Say, is abundant in the intertidal and shallow subtidal zone of the eastern United States (Weimer and Hoyt 1964), C. tyrrhena (Petagna), is typical of the partially protected marls and muddy sands of the very shallowest Infralittoral (2 - 3 m) of the Mediterranean (Peres and Picard 1958), C. australiensis of the sheltered intertidal lagoons of the east coast of Australia (personal observation), while C. stebbingi is very common in muddy sand between 25 and 35 m depth in the North Sea (Schafer 1962). Probably all, but certainly C. tyrrhena can withstand considerable influxes of fresh water.

MOLLUSCA

Gastropoda

Gibbula aquitanica (Trochidae) Cossmann and Peyrot

Mode of Occurrence: Scattered specimens occur in 14 limestone, calcareous sand and calcareous sandstone units, and are preserved as moulds usually complete (figure 2.3a(i)).

Geographic Distribution: It occurs throughout the Marada and Zelten sections and in the calcareous sandstones on the south side of the Jebel Zelten.

Ecology: living species of Gibbula are herbivorous epibionts occupying brackish water lagoons and normal marine beaches down to 10 metres depth. In the Mediterranean they are typical of the Infralittoral pebbly biocoenosis.

Turreted Gastropods

(a) Turritella and Cerithium spp.

The species represented are:-

Turritellidae: Turritella terebralis Lamarck (the most abundant species) (figure 2.3a(ii)).

T. turris Basterot.

*T. (Haustator) vermicularis Brocchi, (living, Senegal)

T. (Archimediella) dertonensis Mayer.

T. (Archimediella) pythagoraica Hilber.

T. (Zaria) subangulata Brocchi (figure 2.3a(iii)).

Cerithiidae: *Cerithium vulgatum Brugière, (living, Mediterranean)

C. (Ptychocerithium) bronni, Partsch.

C. sp.

Mode of occurrence: These occur in 145 limestone and calcareous sandstone units and are usually rather rare. They are preserved as moulds of 2 - 3 whorls lying on their sides, often filled with material finer than the surrounding sediment. The latter represent recycled specimens from eroded lime mud horizons. In limestones the specimens are often fragmented but in many finer beds complete specimens represented by casts with moulds of the largest whorls occur. It is these specimens that give rise to the recycled moulds. At the base of section 22 a 15 cm thick silt crowded with decalcified Cerithium sp., all complete and lying parallel to the bedding, passes within 25 metres into a calcareous sandstone. This re - presents an estuarine mud and sand flat.

Geographic Distribution: These gastropods are present throughout the Marada, Zaggut and Zelten sections and in the calcareous sandstones of the Jebel Zelten.

Ecology: Turritellids are tropical and subtropical shallow water diatom grazers, occurring on a wide variety of substrates, stable or otherwise. Sharply sculptured forms like the fossil Zaria subangulata tend to be intertidal. Senes (1965) regarded Turritella turris as a brackish water indicator.

Cerithiids are typical of mud banks near the mouths of large tropical and subtropical rivers. Many can tolerate lowered salinity and even influxes of fresh water. C. vulgatum Brugière occurs in the polyhaline - marine range (10 - 30°/$_{oo}$ salinity) in the lagoons of the Rhône delta and on the beach and shelf to a depth of 10 metres.

(b) Terebralia and Pirenella

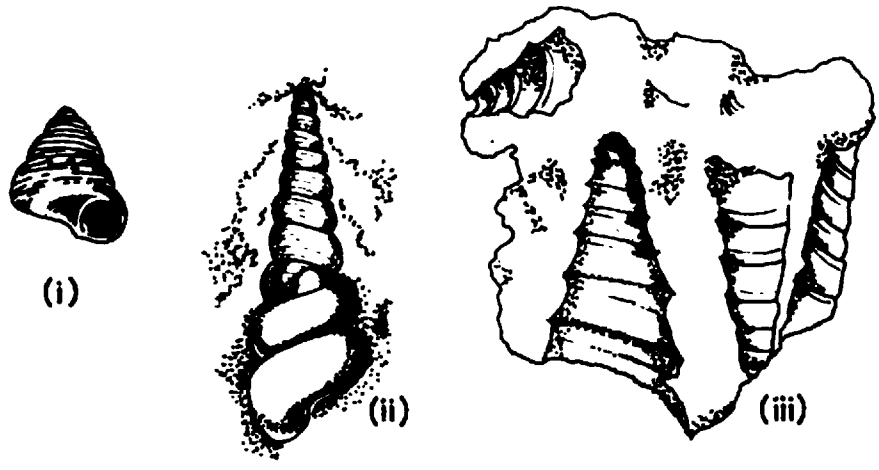
Mode of Occurrence: These are usually rare, occurring in widely scattered beds. At Garet-el-Beda, however, 30 Kms due south of section 39, a coquinais crowded with small, but complete 0,7 cm long casts and moulds of Pirenella with a rich associated gastropod and bivalve fauna. The crowding of a bed by one species suggests a brackish environment. The species are:-

Terebralia bidentata (Defrance)

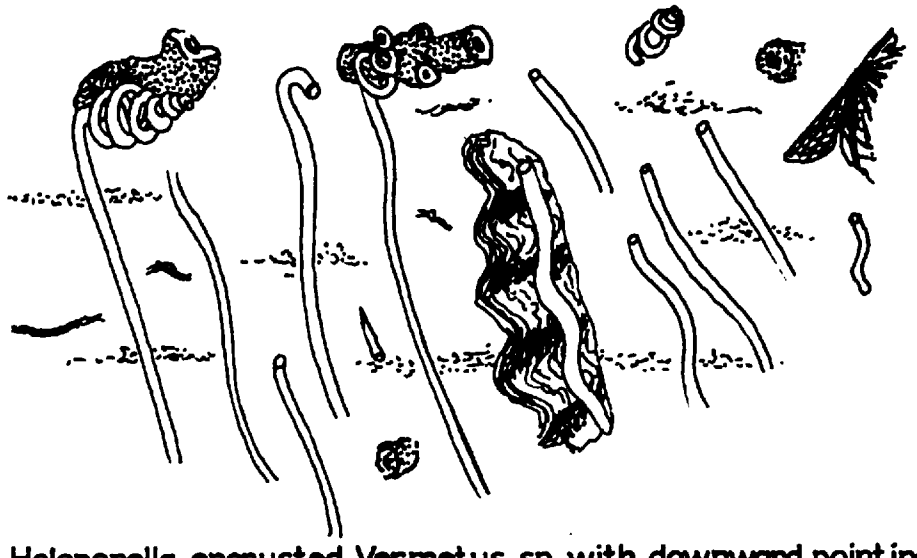
Pirenella plicata (Brugière)

Geographic Distribution: Very scattered specimens occur in units towards the tops of the Marada and Zelten sections, and towards the bottoms of the Zaggut and Jekel Zelten sections and indicate a tendency to die out both north/south and east/west.

Ecology: Living species of Pirenella are found in lagoons and very shallow waters of the tropics. Senes (1965) listed both species present in the Marada group as indicative of brackish water conditions in the



a (i) Gibbula aquitanica Cossmann and Peyrot
(ii) Partially filled mould of Turritella terebralis Lamarck (x1) Section 9
(iii) Moulds of Turritella (Zaria) subangulata Brocchi (x1) Section 19



b Holoporella-encrusted Vermetus sp with downward pointing components (x0·5) Vertical face of calisiltite, Section 5



c Vermetus sp. within crusteous calcareous algae (x1) Section 17

Figure 2.3

Burdigalian, along with several other species recognised from the Zelten area:-

Ostrea crassissima (probably = Crassostrea gryphoides)

Ostrea edulis var. Adriatica

Anomia ephippium var. Ruguloso-Striata. Brocchi.

Cardium edule Linnaeus

Spisula subtruncata Da Costa

Pirenella plicata (Brugière)

Terebralia praebidentata Senes.

Turritella turris Basterot.

Hydrobia sp.

Vermetus sp. (Vermetidae)

Mode of Occurrence: Vermetus sp. occurs in 25 limestone and calcareous sandstone units associated with a stenohaline marine biota. It is always decalcified and bears a longitudinal groove on the smaller whorls. Normally 1.5 cm long tightly, but irregularly coiled individuals with o.1 to 0.2 cm diameter whorls occur jumbled in the sediment, but in a few cases larger specimens are preserved in life position. In a calcisiltite at section 5, horizontal levels with highly coiled Holoporella encrusted whorls, 0.3 cm in diameter, give rise to long and straight or slightly meandering downward pointing components over 30 cm long. They dip at an average of 30° from the vertical westwards (in the top part of the unit) or eastwards (in the bottom half) (figure 2.3c). At sections 17 and 18 (figure 2.3b) a calcisiltite is rich in Vermetus within the skeletons of crusteous calcareous algae (some possibly soft and not preserved). Close coiling persists into the large 2,0 cm diameter whorls in some cases.

Geographic Distribution: Vermetus sp. is present at the tops of the Marada sections, nearer the middle of the Zelten sections and low in the Zaggut sections.

Ecology: Vermetus is a temperate and tropical suspension feeding genus, living attached to algae or shells, embedded in sponges or forming gregarious reefs in open clear waters of moderately high energy. In the Mediterranean it occurs on the non-depositional hard substrates of the Infralittoral.

Strombus bonellii var. praecedens Schaffer (Strombidae)

Mode of Occurrence: Rare moulds occur in 8 units, mainly limestones and calcareous sandstones, associated with a marine and brackish water biota (figure 2.4a(i)).

Geographic Distribution: Its distribution is very patchy, but is limited to the area near Zelten and to the calcareous sandstones of the Jebel Zelten.

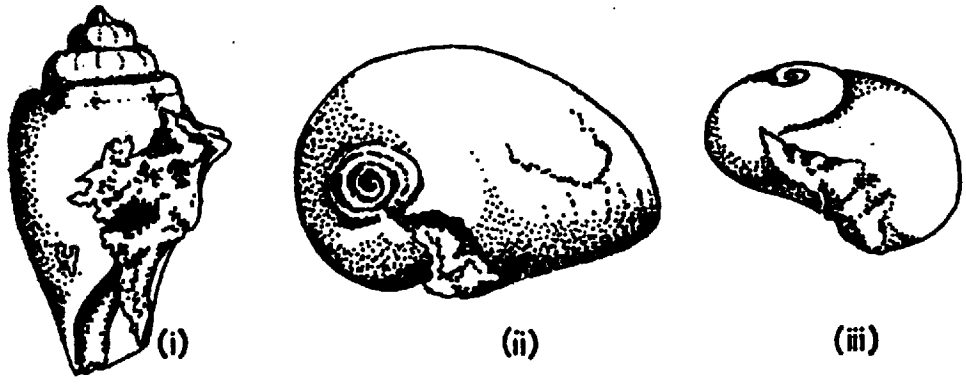
Ecology: Strombus lives in shallow tropical waters on sandy bottoms, scavenging and browsing on weeds. Its associates and distribution suggest that S. bonellii var praecedens could tolerate lowered salinity.

Cypraea subovum: d'Orbigny (Cypraedae)

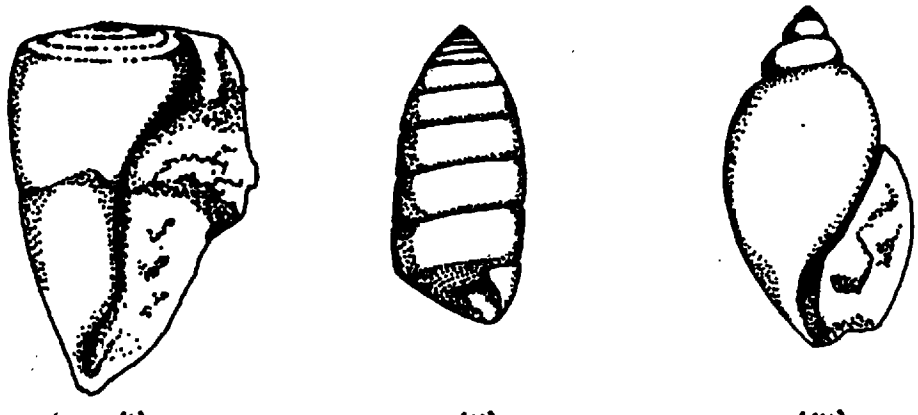
Mode of Occurrence: This is found in 21 units, largely limestones and calcareous sandstones, as complete or slightly broken moulds. It is never in position and is always rare (figure 2.4a(ii)).

Geographic Distribution: It is present in the central parts of the Zaggut and Zelten sections and there are scattered occurrences in calcareous sandstones in the Jebel Zelten and Marada sections.

Ecology: Cowries are tropical and rarely temperate herbivorous epibiontsliving on ledges and grassy sandbanks in fully marine clear water.



a (i) Strombus bonellii var praecedens Schaffer, (x1·5) Section 18
(ii) Cypraea subovum d'Orbigny, (x1) Section 30
(iii) Natica sp. (x 0·75) Section 33



b (i) Conus melficus Desio, (x1·5) Section 16
(ii) Buliminus sp., (x4) Section 17
(iii) Ampullospira sclaris (Bellardi and Michelotti), (x1) Section 18

c Group of small Crassostrea gryphoides Schlotheim with Balanus.

Section 17.



Figure 2.4. gastropod moulds

Natica spp. (Naticidae)

The following species occur:-

* Natica millepunctata Lamarck, (living, mediterranean) (figure 2.4a(iii)).

Natica sp.

* Polinices josephina Risso (living, mediterranean).

Mode of occurrence: Isolated and rare decalcified examples occur in eleven limestone, calcareous sand and sandstone units.

Geographic distribution: They are present near the middle of the Zelten sections, in the calcareous sandstones of the Jebel Zelten and towards the base of one Zaggut section.

Ecology: Naticids are very shallow water and intertidal epifaunal and infaunal carnivores. N. millep uncata occurs on the intertidal sandy muds and beaches of the Rhone delta, while P. josephina is typical of the beach and Infralittoral terrigenous sand biocoenosis at depths of ten metres.

Conus spp. (Conidae)

The following species are present:-

Conus (Lithoconus) mercati Brocchi (commonest).

C. (Dendroconus) melficus Desio (figure 2.4b (i)).

C. berghausi Michellotti.

C. (Chelyconus) clavatulus Lamarck.

C. (Rhizoconus) virginalis Brocchi.

Mode of occurrence: Complete or slightly broken moulds are scattered in twenty one units, usually limestones.

Geographic distribution: They are present near the tops of the Marada and Zelten sections, the bottoms of the Zaggut sections and in a few calcareous sandstones in the Jebel Zelten.

Ecology: Living species of Conus are tropical carnivores, feeding

on fish, molluscs and worms. They inhabit hardish substrates of sand or rock in fully marine shallow waters.

Buliminus sp. (Pulmonata) (figure 2. 4b(ii))

Mode of occurrence: Buliminus is rather rare, scattered in ten limestone, calcareous sand and sandstone units associated with a marine and brackish water biota. In an exposure of interlaminated sands and shales 10 km. west of section 7, a large number of individuals occur in thin rippled sandy interlaminae associated with a clearly mixed fauna of Crassostrea and Turtle Bone. Sadek (1923) found a fresh water fauna including Buliminus in the U. Miocene of Egypt.

Geographic distribution: It is restricted to a fairly constant level just below the Id m onea horizon in the Zelten sections, and low in the Zaggut sections, at Jebel Auf, and in the Jebel Zelten. It dies out both north/south and east/west.

Ecology: Living Buliminus are continental, so the presence of this form in marine sediments is probably an indicator of mixing or intertidal conditions. Its absence from fluvatile beds, and relative abundance in calcareous sands and shales, suggests that it inhabited the intertidal zone, perhaps the very top.

There are in addition a number of gastropods, never common, that are listed only. The names are followed by a list of the biofacies in which they occur.

Fissurellidae

Fissurella graeca linnaeus: This occurs in five units (bivalve-gastropod and Placenta biofacies).

Ecology: fissurella is an epibiont, browsing on algae on hard substrates from low tide to a few metres depth in normal marine water.

Trochidae

Oxystele orientalis Cossmann & Peyrot: Two units (Idmonea and Capsa biofacies).

Ecology: This is a browsing herbivorous epibiontic genus, widespread in Europe, Africa and the Pacific.

Calyptraeidae

Calyptraea sp.: Two units (bivalve-gastropod and ribbed bivalve biofacies.

Ecology: Calyptraea is also a browsing herbivorous epibiontic genus, that occurs in shallow waters on all substrates.

Hydrobiidae

* Hydrobia ventrosa (Montagu): Two units (bivalve-gastropod and ribbed bivalve biofacies).

H.sp. Occurs in one outcrop (continental biofacies).

Ecology: H. ventrosa is cosmopolitan and herbivorous. H. sp. occurs associated with leaves in a green shale at an outcrop 7·5 kms west of section 30, but is ferruginised and poorly preserved. Its asso - ciation and geographic position suggest that it is freshwater.

Naticidae

Ampullospira scalaris (Bellardi & Michelotti): Five units (mainly ribbed bivalve biofacies) (figure 2. 4b (iii).

Ecology: Naticids are carnivorous epi- and endobionts.

Nassariidae

Nassa turonensis Deshayes: Occurs once (bivalve-gastropod biofacies).

Ecology: Nassariids are scavengers and carnivores living at all depths.

Fasciolariidae

Fusus clavatus Brocchi: Three units (bivalve-gastropod biofacies).

Ecology: Fasciolariids are tropical and temperate carnivorous epi- and endobionts.

Turridae

Clavatula camillae (Hoernes): Four units (bivalve-gastropod and Corbula basteroti biofacies).

Ecology: Turrids are carnivorous.

Terebridae

Terebra sp.: Once only (Capsa biofacies).

Ecology: Species of Terebra are shallow (burrowing in sand) carnivores found in the tropics and temperate parts of the world.

The closest association of these gastropods, is with smooth and ribbed bivalves and Capsa lacunosa.

Scaphopoda

Dentalium sp.

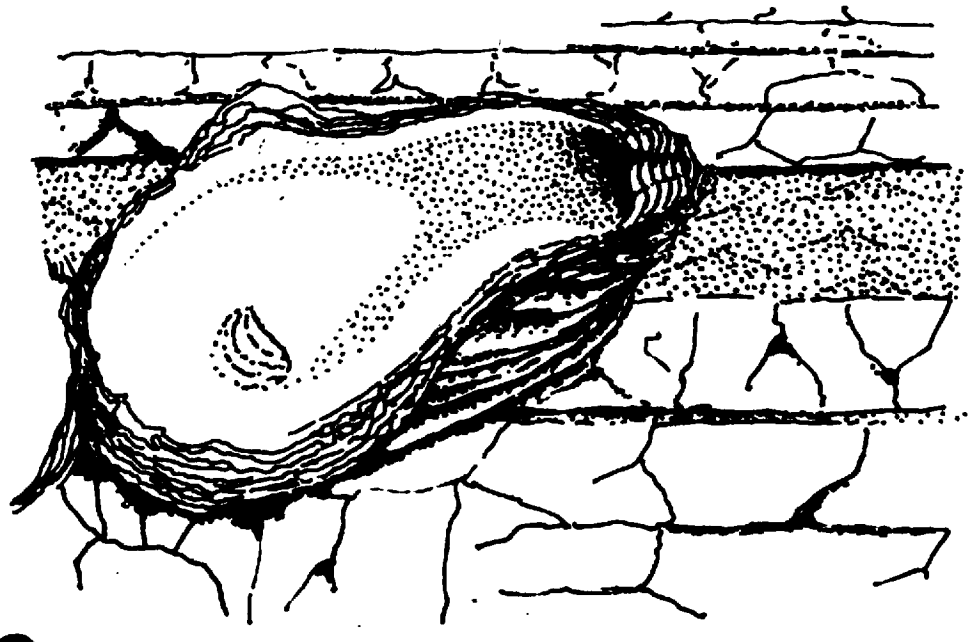
Geographic distribution: This occurs once, in a calcareous sand - stone on the south side of the Jebel Zelten.

Ecology: Scaphopods are carnivorous and scavenging inbionts found in the tropics.

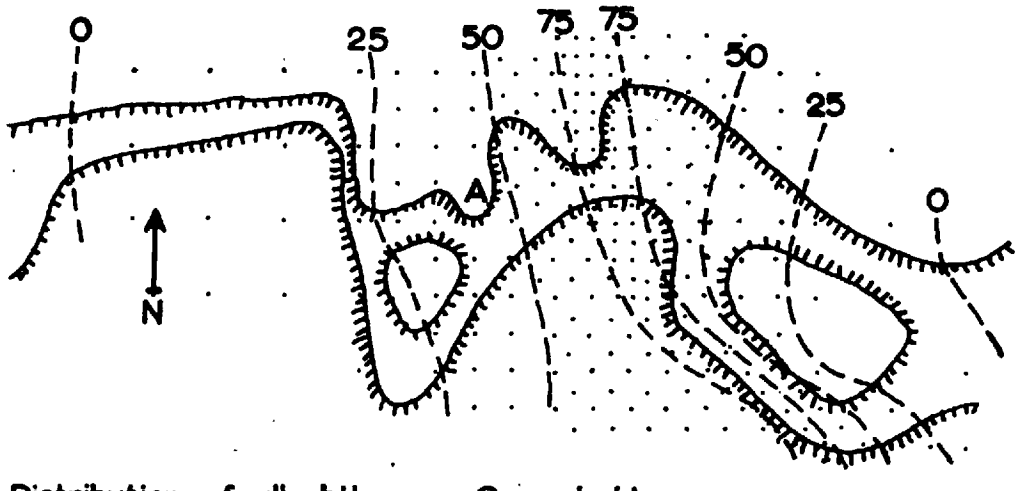
MOLLUSCA

Bivalvia

Crassostrea gryphoides Schlotheim (Ostreidae): This species occurs commonly and often abundantly in 195 units, mainly limestones and cal - careous sands. In the nine units (5%) in which it is preserved in life



a Pear-shaped Crassostrea gryphoides individuals in interlaminated calcareous sands and shales. (x 0·5) Section 7



b Distribution of allochthonous C. gryphoides in shale unit 50metres wide and 50 cms thick. 400m E. of Section 7.

(above) Contours drawn on thickness of oyster bed in cms.

(right) Vertical section at A showing oysters interfingering with shale.

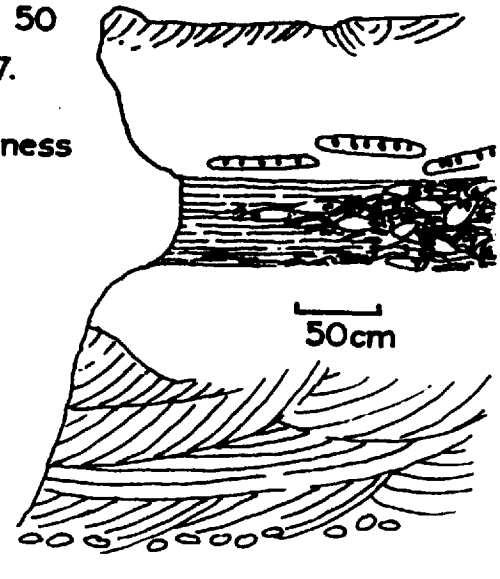


Figure 2.5

position it is based on limestone seven times and shale twice, and its containing sediment is limestone eight times and sand once. In 20% of the units it is bored by Polydora ciliata (figure 2. 2b) and Cliona megastoma.

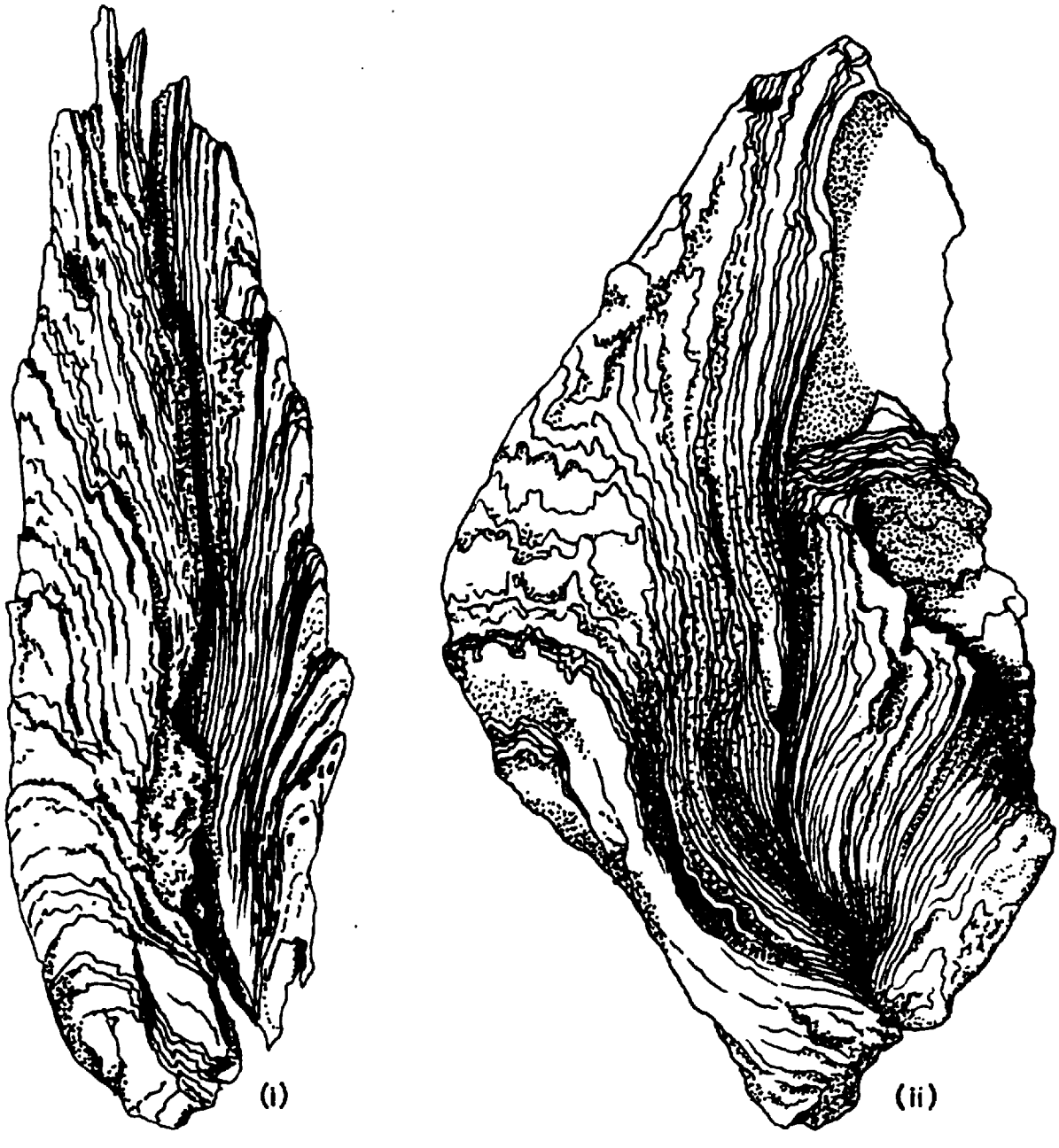
There are four types of preservation:-

a) Scattered individuals obviously not derived from major con - centrations. These are by far the most common, and consist of alloch - thonous pear-shaped oysters (e.g. 10 cm long x 6 cm wide x 1·5 cm thick) isolated or in small clusters in sands, interlaminated beds and lime - stones (figure 2. 5a). They are often encrusted with Electra elliptica, and Balanus concavus and are normally disarticulated. Platey fragments 2·0 x 3·0 cm consisting of individual growth lamellae are commonest, but are mixed with complete specimens and obviously have not travelled far. Some may be derived from preservation types (b), (c) or (d) but probably most represent small non-reef groups or clusters and isolated individuals.

b) Beds up to 30 cms thick composed of jumbled oysters and oyster fragments. A range of growth forms is exhibited by the complete speci - mens. Often the bed is based on soft fine-grained sediment and there are a large number of large flat-lying thick-shelled geniculate gryphaeoid types (12 x 5 x 4cm). Pear-shaped forms predominate in beds based on disconformities marked by clay-pellet conglomerates. Spoon-shaped forms characterised by long ligamental areas and a swollen, almost circular distal end, obviously grew upwards through a thick mass of oysters or soft mud until they reached a suitably aerated and nutrient-rich level. A few beds in section 17 and 18 contain very small Crassostrea only (figure 2. 4c), individually and in groups of up to forty. They pro - bably represent stunted forms developing in severely restricted conditions. Though nearly all are allochthonous and 2 - 3cm diameter fragments are very common, the beds usually die out laterally within a few hundred



Photo. 2.2. Autochthonous reef of Crassostrea gryphoides Schlotheim showing inverted banana hand habit. Section 17



(i) Vertically disposed Crassostrea gryphoides Schlotheim (elongate form) from autochthonous reef. (x 0·75)

Section 17

(ii) Horizontally disposed thick shelled individual from the base of the same bed. (x 0·85)

Figure 2.6

metres, so the bed more or less marks the actual site of the original oyster bank. Throughout many of the beds small groups of up to twenty individuals joined together, are still in life position; they are either pear- or spoon-shaped or simply elongate and point vertically with their umbones at the base. Polydora ciliata borings riddle many of the shells. Allochthonous disarticulated oysters aligned between 210° and 270° occurring in section 18, indicate currents flowing southwestwards or northeastwards.

The rapid lateral dying out of oysters and oyster fragments is well illustrated by a Crassostrea bed exposed 400 metres east of section 7. A north-south trending shale unit 100 metres wide overlies and incorporates an allochthonous oyster bed 150 metres wide. A total thickness of 25 cms of oyster dies out in 50 metres. (see figure 2. 5b).

c) Large reefs (bioherms) of Crassostrea in life position. At section 17 a metre thick reef is persistent for 700 metres east/west. It is founded on very thick flat lying articulated gryphaeoid types 17·5 x 15 x 5 cm (figure 2. 6(ii) and photo 2. 3b) with very irregular surfaces. Throughout the rest of the thickness the oysters are thin, flattened and very elongate on average: 19 x 7·5 x 2·5 cm (figure 2. 6(i)). All are articulated and in growth position pointing vertically upwards (umbones down) with a slightly convex shell so that there is an oval gape at the top (photo 2. 3a). Very elongate forms are typically autochthonous (fig 2. 8a) and represent an attempt to reach the most favourable conditions ,as in preservation type (b). The individuals are based upon each other and often 10 - 15 closely applied specimens grow on the shell of one or two, so that the whole resembles a series of inverted banana hands, separated by rare sandy areas without oysters (photo 2. 2). At the base the first layer of upward pointing types are either broken off at 12 cm and are still pointing straight up, or are bent over 75° from the vertical. Throughout the reef the oysters



Photo. 2.3a. Top view of autochthonous Crassostrea gryphoides reef showing gape of the valves. x0·1. Section 17.



Photo. 2.3b. Bottom view of autochthonous Crassostrea gryphoides reef showing thick gryphaeoid types. (x0·15) Section 17.





(above) Southward facing vertical section of calcarenite at Section 5 with Crassostrea gryphoides reef on the edge of a channel (right). Note the rapid diminution from complete specimens to fragments and the sinking of the reef into the substrate.

(left) Typical group of upward pointing individuals showing inverted banana hand habit.

Figure 2.7

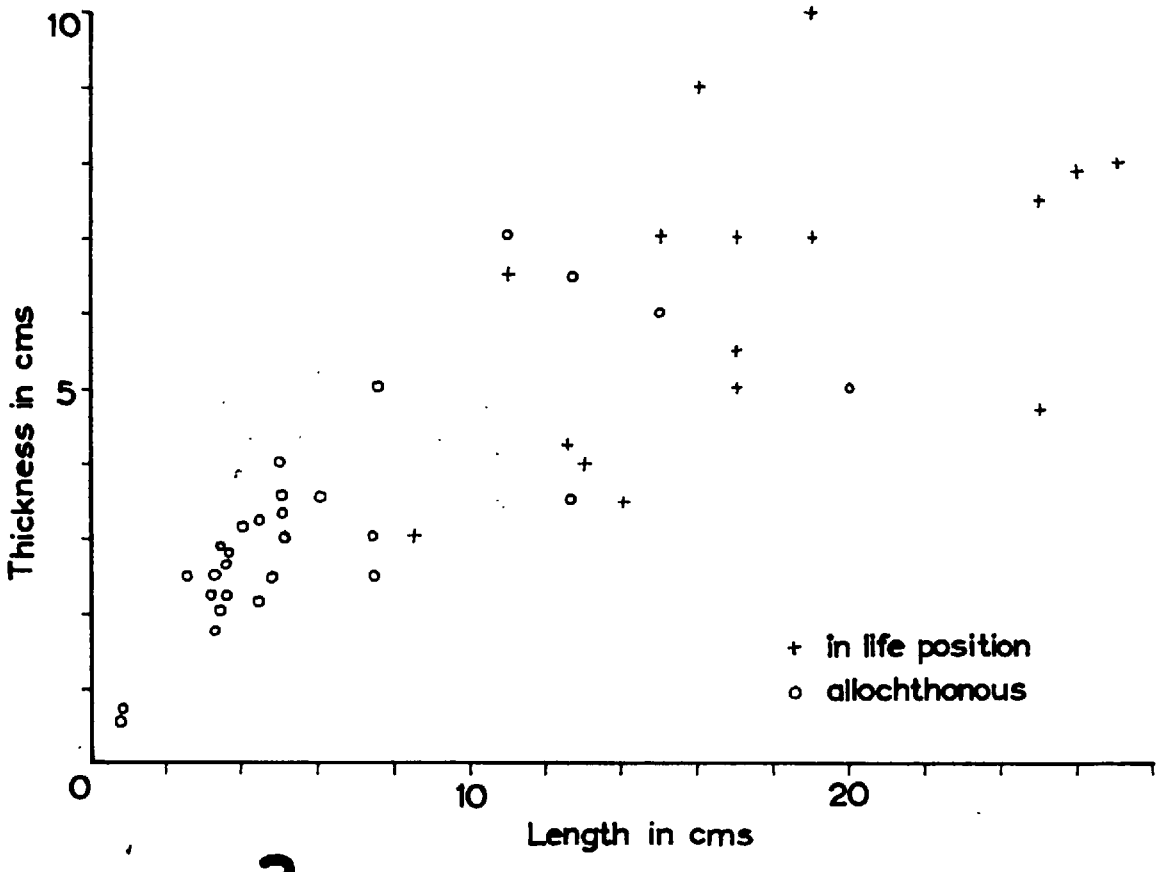
are oriented 210° southwestwards, inclined 40° to 52° away from the vertical. Both these features indicate the presence of strong currents flowing from a northeasterly direction. Most of the elongate oysters are extensively Polydora bored, and separated from each other by a large quantity of fragmentary lamellae. Reefs of (c) type preservation pass into (b) type through beds up to one metre thick with only a few scat - tered vertical sequences of autochthonous individuals.

d) Smaller reefs on the banks of limestone channels. At section 5 a metre thick bed on the edge of a channel is persistent for only 30 metres laterally. The form and habit of the oysters are similar to those of preservation type (c) but include many (40%) smaller, thinner, slightly sinuous forms (11 x 7 x 2 cm). The high energy of the condi - tions is well illustrated by the rapid lateral transition from complete specimens to nothing, fragments occupying a very thin zone (figure 2. 7).

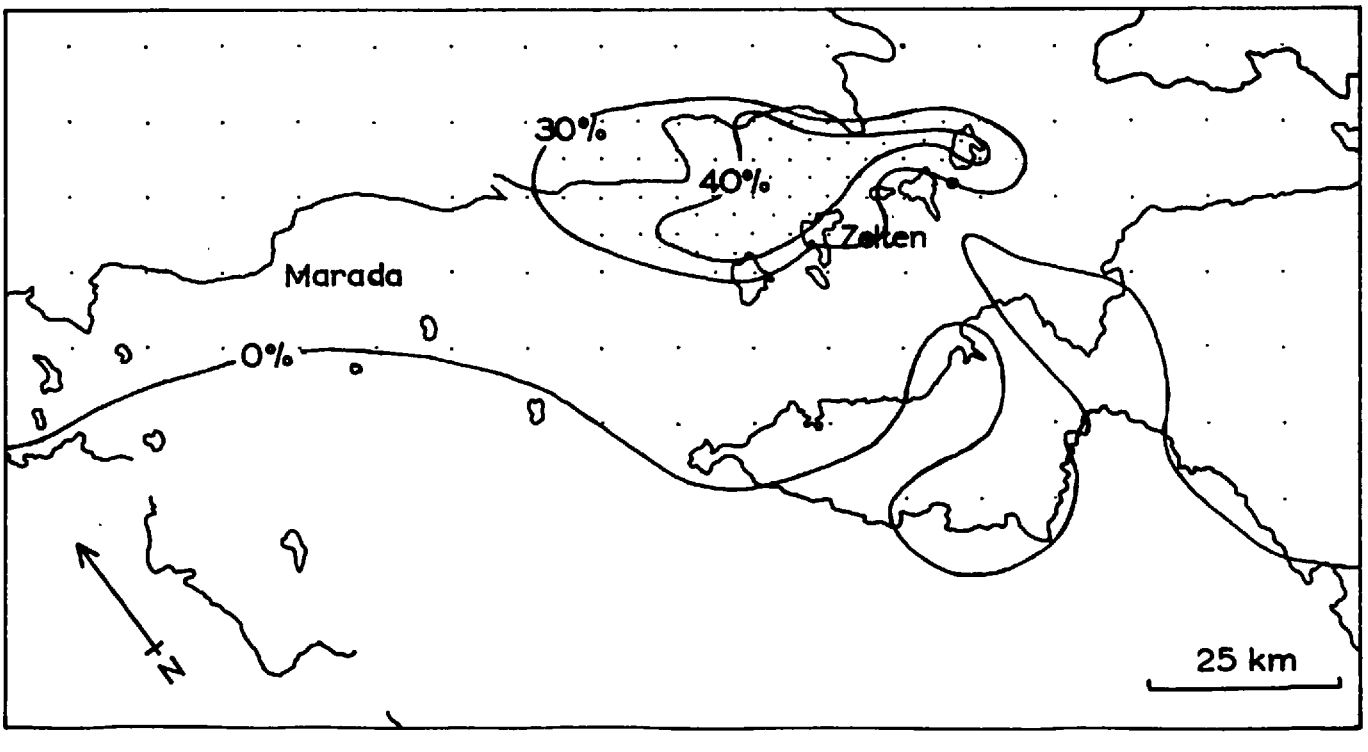
Geographic distribution: C. gryphoides is extremely widespread, and present at the top of the Marada sections, throughout the Zaggut and Zelten sections and scattered through the calcareous sandstones of the Jebel Zelten.

Ecology: Crassostrea gryphoides is the Miocene representative of a line of Tertiary to Recent coralline oysters which includes the Palaeogene Ostrea longirostris and the living Gulf of Mexico oyster, Crassostrea virginica. A number of names have been given by various authors for the growth forms of Crassostrea gryphoides, and commonly the generic name Gryphaea has been used.

Broad or geniculate forms:	Gryphaea gryphoides var gingensis	Dollfuss & Dautzenberg.
	Gryphaea (Crassostrea) gingensis	Cossmann & Peyrot.
Straight, very elongate forms:	Gryphaea (Crassostrea) aginensis	Cossmann & Peyrot.
	Ostrea gryphoides var crassissima	Dollfuss & Dautzenberg
Straight, elongate with long ligamental areas:	Crassostrea gryphoides var angustata	de Serres.



a Graph of random selection of C.gryphoides specimens to show that elongate thick shelled individuals more frequently occur in life position.



b Percentage distribution in sections of Crassostrea gryphoides Schlotheim

Figure 2.8

The ecology can be related directly to that of Crassostrea virginica, which in its capacity to develop anywhere individually, in isolated clumps or to form extensive reefs, seems to closely parallel the behaviour of Crassostrea gryphoides. C. virginica is a suspension feeder, existing in areas of non-deposition. Permanent communities of oysters develop between the heads of estuaries and the open sea where the salinity varies from 10‰- 30‰. A stable floor is necessary, preferably of sticky, cohesive mud, though sand is tolerated in well sheltered areas. Four salinity-controlled environments are represented:

1) Heads of Estuaries: 0 - 15‰ salinity:- small smooth shelled forms without borings.

2) 10 - 20‰ Salinity:- a large population of smooth and densely packed shells of narrow shape. Polydora and sponge borings and Mytilus, Balanus and Chlamys are common. The maximum development of oysters is between these salinities.

3) 25‰ (range 10‰ - 30‰):- near the mouths of estuaries. Gives a good growth of massive eroded shells. Shells have concentric ridges, and many borings of Polydora, Cliona and predators.

4) Near normal salinitiesnear the junction of estuaries with the open gulf. A sparse population of heavily bored slowly growing forms develops.

The parallel between the modes of occurrence of C. gryphoides and C. virginica is so close that these environments may be related to the preservation types of the former.

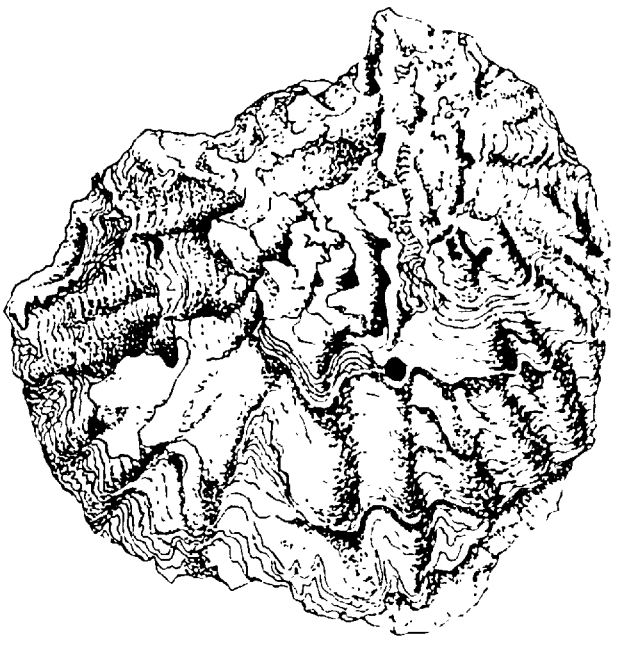
The small C. gryphoides of sections 17 and 18 included in preservation type (b) probably belong to environment 1, while the beds and reefs of preservation types (b), (c) and (d) belong to environments 2 and to a lesser extent 3. The isolated individuals of (a) probably developed either in environment 4 or in small clusters near low tide.

Crassostrea virginica develops best between 0 and 27 metres depth though those living at or near low tide are scattered. Low ridged reefs with their long axes normal to the prevailing current develop from shell clusters in suitable conditions in bays, estuaries and near shore areas. The most suitable conditons are where the bottom is stable and the water not exposed to wave action nor too fresh. Often individuals sink into the mud under the weight of the shell, a feature seen in C. gryphoides (fig.27). Members of the Crassostrea virginica reef association include calcareous algae, Crepidula, other oysters, Mytilus, Balanus, Bryozoa, crabs, Anomia and predaceous gastropods.

A great range of temperature is tolerated, 2° - 30°C, but spawning and therefore reproduction can only take place when the water temperature reaches 20°C.

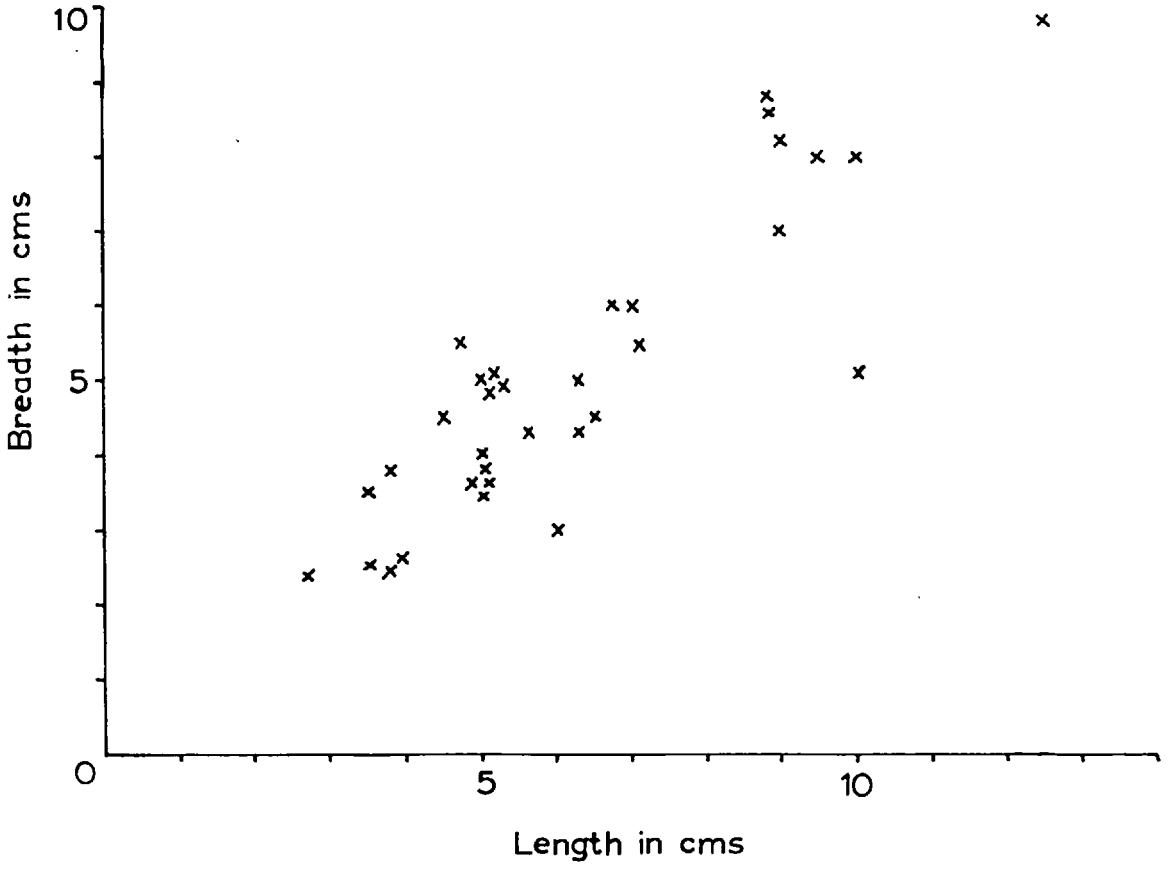
Lopha plicatula (Gmelin) (Ostreidae) (figure 2.9a)

Mode of occurrence: This species has a cellular shell structure characteristic of the genus Lopha (Pychodonta). It occurs in 101 units, largely limestones, but never calcareous sandstones. It is usually rare or common, but when abundant a large number of disarticulated broken and unbroken individuals set in a matrix of 2-3 cm diameter fragments crowd the bedding. On average 10% are complete, articulated and joined in clumps of 2 or 3. Clumps of upward pointing L. plicatula in life position were recorded in 4% of occurrences. In these cases the basal substrate was fine grained limestone (75%) and shale (25%), and the containing sediment was limestone. A sharp geniculation near the umbo of many specimens, indicates a gryphaeoid trend associated with a softer substrate. Cliona borings affect 12% of the occurrences. Banks of L.plicatula are often 50 - 100 metres across but thick reefs like those of C.gryphoides never occur, the beds being only one individual thick, and the shells never growing on one another. The shape variation is



a Lopha plicatula (Gmelin). (x1)

Section 8



b Graph of length against breadth of 'Lopha plicatula, showing straight line relationship. Random selection of specimens used.

Figure 2.9

linear, showing the presence of one species only. D.plicaluta virleti recorded from this area (an elongate form) is absent (figure 2. 9b).

Geographic distribution: It is found throughout Dor Zaggut and the middle parts of the Zelten sections.

Ecology: D.plicatula is very similar to Lopha (Pycnodonta) hyotis a living species from the tropical Atlantic, Indian and South Pacific Oceans, some specimens being indivisible. Lopha hyotis is a suspension feeding fully saline tropical oyster, living between 0 and 90 metres depth. (The size of the Zelten specimens of D.plicatula suggests depths between 7 and 30 metres). A hard cohesive mud substrate is not essential, and it can develop on banks of soft lime mud. It is not a reef-former, rather occurring as collections of individuals.

Ostrea Edulis-like forms (Ostreidae)

These include a number of closely related nominal species and varieties:-

Ostrea fimbriata Grateloup

O. edulis var bobleyi Deshayes

O. frondosa var kohlfsi Fuchs (figure 2. 10a)

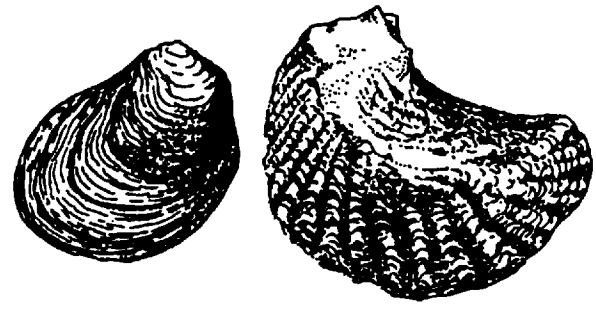
O. digitata Eichwald

Mode of occurrence: They have a patchy distribution, usually occurring as rare accessories in beds rich in other oysters (C. gryphoides, L. plicatula). They form a bed 15 - 20 cm. thick at section 8 where specimens 9 x 7·5 x 2·5 cm are abundant. Many are upward pointing and joined in clumps of 3 or 4, but this may be due to crowding as few are still articulated. A matrix of fragments surrounds all the shells.

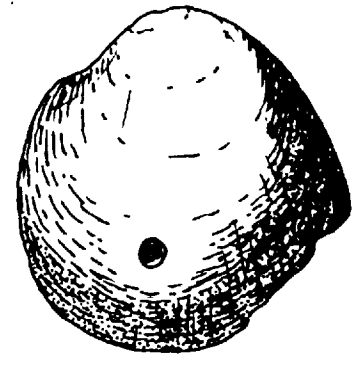
Geographic distribution: The group occurs largely north of Zelten and Marada, where it is present throughout the Zaggut sections and in the central parts of the Zelten sections.



a Ostrea frondosa var rohlfsi Fuchs. (x1) Section 5



b Ostrea frondosa var subfimbriata Sacco. (x1)
Section 6



C Anomia ephippium var ruguloso-striata Brocchi. (x1)
Section 7.

Figure 2.10

Ecology: Ostrea edulis occurs today in sub-tropical and temperate waters, generally from low tide to 50 metres depth (especially 0 - 30 m), on comparatively stable non-depositional bottoms of mud, rock, sand, and muddy gravel . The optimum salinity varies between 31 and 35‰. In the Mediterranean it lives in the Ulva corallina zone in depths of 6 to 12 metres.

Ostrea frondosa var subfimbriata Sacco (figure 2. 10b) (Ostreidae)

Mode of occurrence: This is a rather rare species occurring in limestone units, but it is dominant in some one metre thick beds. Articulated specimens are distributed evenly through the unit in rather low density. They probably developed well apart from each other and have not been disturbed since deposition.

Geographic distribution: It is present patchily throughout the Zaggut sections, and concentrated near the middle of the Zelten and Jebel Zelten sections.

Ecology: The distribution and associated biota are very closely comparable with those of the O. edulis group, so that although there is no closer relative than O. edulis the ecology may be extrapolated from there. Three other species of oyster are present in the area but are very rare: -

Ostrea lamellosa Brocchi

O. (Ostreola) sollomacensis Cossmann & Peyrot

O. forskalii Chemnitz var undulatior Sacco

Chlamys spp. (Pectinidae): Chlamys is represented by four species, three of which are widespread throughout the area.

Chlamys praescabriuscula Fontannes
(size 4·3 long x 4·0 wide x 1·0 valve inflation) (photo 2. 4b)

C. Praesabriuscula zitteli (Fuchs) (size 3·2 x 2·8 x 0·6) (photo 2.4c)

C. submalvinae Blanckenhorn (3·8 x 3·5 x 1·0)

C. multistriata Poli (2·2 x 1·8 x 0·3) (photo 2.4d)

Mode of occurrence: Disarticulated complete, broken or fragmented specimens are common in many limestone units but are rarely abundant. Chlamys praescabriuscula and C. praescabriuscula zitteli are very common, C. multistriata rather less so, and C. submalvinae is rather rare.

Geographic distribution: Chlamys occurs throughout the Zaggut and Zelten sections, and is present in the calcareous sandstones of the Jebel Zelten and Marada sections. (figure 2. 16b).

Ecology: Species of Chlamys are cosmopolitan swimming or bysally attached suspension feeders, occurring from low water to 200 metres depth on muddy or gravelly sands and coquinas. Optimum depths are be - tween 8 and 30 metres. Some lowering of salinity is favoured by some species but fresh water is never tolerated.

Pecten and Flabellipecten (Pectinidae)

These are represented by five species:-

Pecten seniensis Lamarck

Pecten incrassatus Partsch

Flabellipecten fraterculus Sowerby

Flabellipecten expansus Sowerby (photo 2. 4a)

Flabellipecten pasinii Meneghini.

Mode of occurrence: The species of Flabellipecten are much more common than those of Pecten, and occur in many limestone units though never abundantly.

Geographic distribution: They are present throughout the Zaggut sections but are restricted to the tops of the Marada sections and the middle of the Zelten sections (figure 2. 16a)

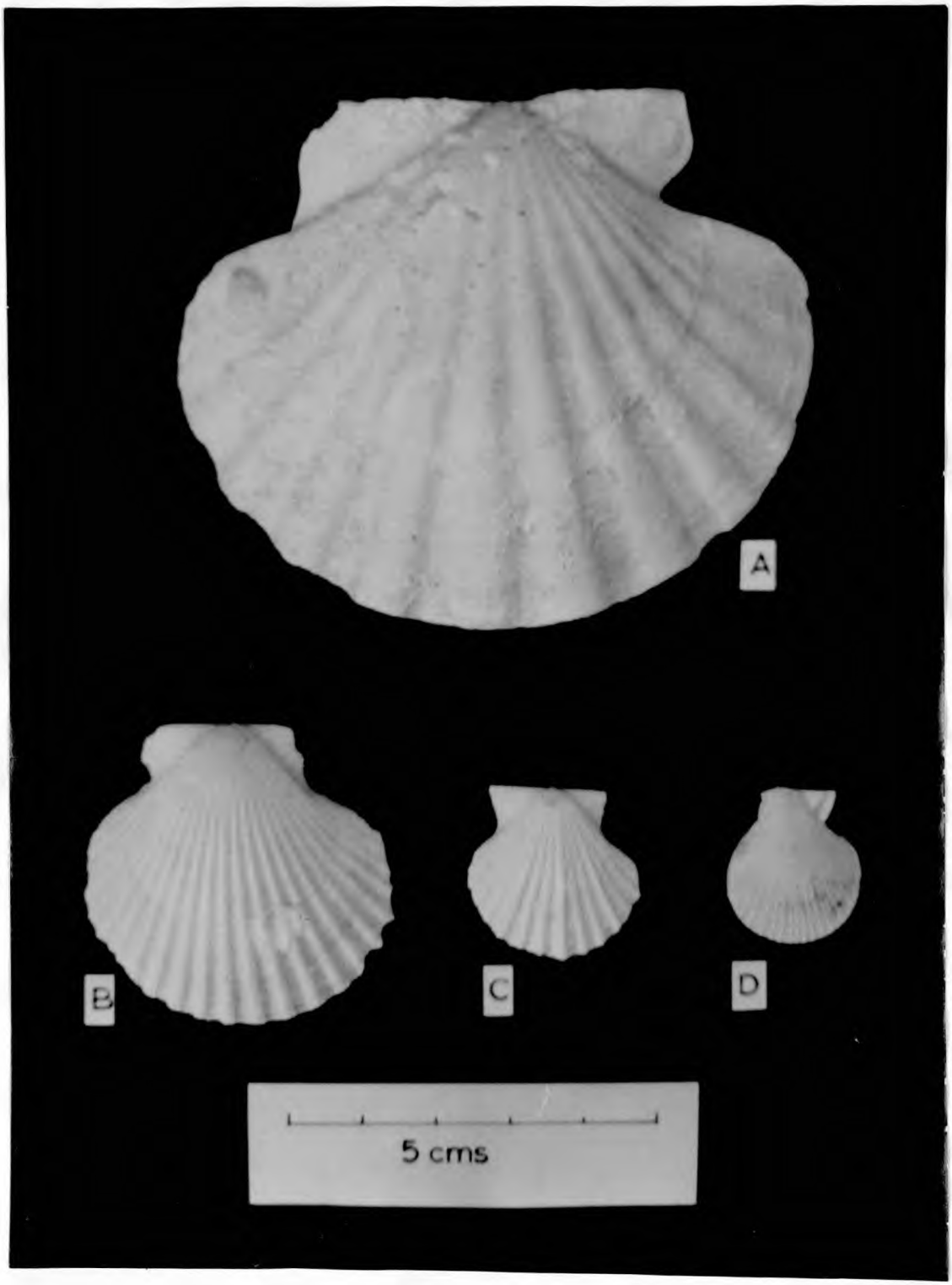


Photo. 2.4. Pectinids.

a. Flabellipecten expansus Sowerby

b. Chlamys praescabriuscula Fontannes

c. Chlamys praescabriuscula zitteli (Fuchs)

d. Chlamys multistriata Poli

Ecology: All the species are similar to Pecten maximus, a tropical to temperate stenohaline species that likes bottoms of clean fine sand, gravel, or muddy sand in waters rather shallower than forty metres.

The distribution and associates of this group suggest that it is much more stenohaline than Chlamys.

* Spondylus crassicosta Lamarck (Spondylidae)

Mode of occurrence: This species is found as a rather rare accessory in 31 richly fossiliferous limestone units. It is typically fragmented but in 22·5% of the occurrences it is still articulated and in 13% it is in life position, umbones pointing downward at about 45° (figure 2. 11a).

Geographic distribution: S. crassicosta occurs at various levels in the Zaggut sections, towards the tops of the Zelten sections and once at the top of a Marada section (2).

Ecology: Living species of Spondylus occur in tropical seas adhering to shells and rocks in shallow, fully marine water. S. crassi - costa is a mediterranean species living at various depths and requiring a firm substrate. The life position of the examples from Zelten suggest that the spines may have supported them in a soft substrate.

Anomia ephippium var rugulosо-striata Brocchi (Anomiidae)(figure 2. 10c)

Mode of occurrence: Isolated disarticulated examples occur in 16 units closely associated with Crassostrea gryphoides (a feature noted by many authors).

Geographic distribution: It is scattered in the Zaggut sections and is present in the lower parts of the Zelten sections.

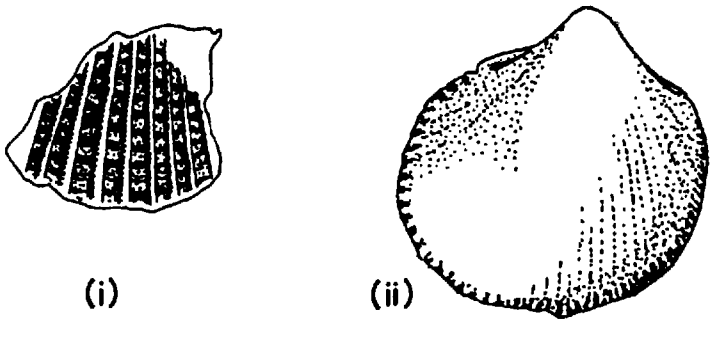
Ecology: Anomia lives bysally attached to shells and pebbles from low water to 146 metres. Near the Rhône Delta it is common on the shelf between 0 and 51 metres (especially 11 - 25 metres) (Van Straaten 1960) Senes (1965) regarded it as a brackish water indicator and its close asso - ciation with Crassostrea supports this view.



a Spondylus crassicosta Lamarck in position of life. Vertical section of calcarenite, section 18 (x1).



b Placenta miocenica crowding limestone bedding vertical face. Section 7.



c (i) External mould of Cardita monilifera Dujardin. (x 2) Section 22

(ii) Internal mould of Cardium multicostatum Brocchi. (x 2) Section 22

Figure 2.11

Placenta miocenica (Fuchs) (Placunidae) (photo 2. 1a and 2. 5a)

See Cox (1962) for a systematic study of this form: probably some specimens are attributable to his species P(Indoplacuna) africana Cox.

Mode of occurrence: It most commonly occurs as fragments but often articulated and disarticulated complete shells crowd beds between 15 and 100 cm thick to the exclusion of everything else (a feature noticed by Stefanini 1929). 90% are parallel or subparallel to the bedding with only a few at high angles to it (figure 2. 11b). Encrustations of Balanus and Electra and borings of Cliona (photo 2. 1a) are common.

Geographic distribution: Placenta is widespread through the middle and lower parts of the Zaggut and Zelten sections.

Ecology: Recent Placunas are suspension feeding tropical epi - bionts occurring from low in the intertidal zone to depths of 20 metres (rarely 30 metres) where they thrive on the sandy mud of tidal flats, shallow bays and mouths of estuaries. They can survive lowerings of salinity and even influxes of fresh water, though too much accompanied by too much mud may kill the population (Allen 1950).

Ribbed Bivalves

(Carditidae and Cardiidae)

Nine species are represented:-

Carditidae:- Cardita crassa Lamarck

Cardita monilifera Dujardin : (common) (figure 2. 11.c(ii))

Cardita sp. (common)

Cardita nuculina Dujardin

Cardiidae:- * Cardium edule Linnaeus (common)

Cardium multicostatum Brocchi (common) (figure 2. 11. c(i))

Cardium kunstleri Cossmann & Peyrot

* Cardium paucicostatum Sowerby



Photo. 2.5a. Placenta miocenica. Interior of shell. Section 11



Photo. 2.5b. Cobble of calcareous silt bored on both surfaces by Gastrochaena squamulosa . Section 25.

Mode of occurrence: Ribbed bivalves are present in many sections and are generally common and complete but only articulated in 7% of cases. In calcareous sandstones they often occur in clay pellet con - glomerates.

Geographic distribution: They are scattered at various levels through most of the sections in the area.

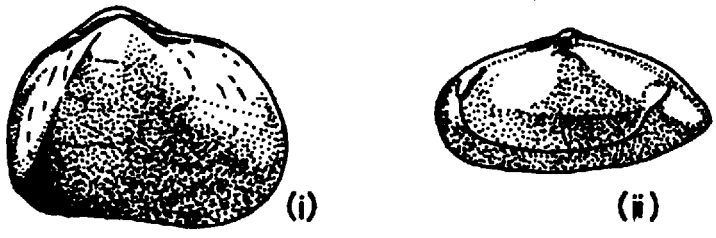
Ecology: Carditids occur in warm seas, at all depths and are largely marine. Members of the Cardiidae indicate shallow marine or brackish water conditions: Cardium edule is Oligohaline, existing in Mediterranean beaches, lagoons, bays and estuaries where the salinity is as low as 17‰. All substrates between 0 and 20 metres are tolerated. Cardium paucicostatum is also a living Mediterranean species, tolerating salinities of 10 - 30‰(Polyhaline-marine) but also thriving on the shelf on sands and muddy bottoms between 11 and 50 metres.

Capsa lacunosa (Chemnitz) (Tellinidae) (figure 2. 12. a(i))

Mode of occurrence: The preservation is unusual in that the speci - mens are nearly always articulated (93·6%). They commonly lie parallel to the bedding in fine calcareous silts, and occur as lime mud moulds associated with clay pellets in calcareous sandstones representing eroded mud flats (35·4%).

Geographic distribution: This is patchy, specimens being distri - buted towards top of Zaggut, Zelten and Jebel Zelten seotions, as well as towards the base of the Zaggut & Jebel Zelten sections. They are present once in the Marada sections. (figure 2. 12b).

Ecology: Capsa lacunosa is a deposit feeding species found in French Guinea and Senegal. From its distribution in the Zelten area it would seem to be a littoral form, living in sheltered sandy mud flats near the mouths of estuaries. Many living Tellines prefer sheltered littoral conditions and some are euryhaline.

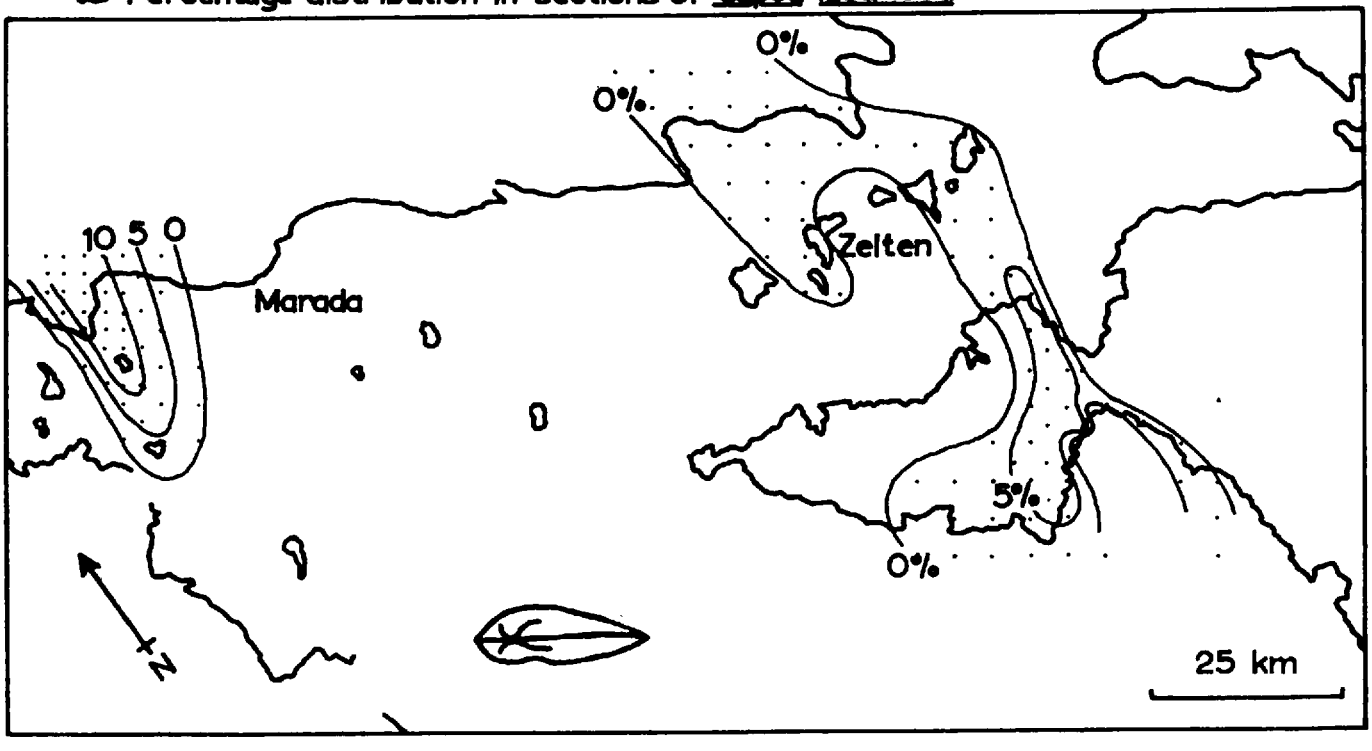


a (i) (ii)

(i) Capsa lacunosa (Chemnitz). (x1) Section 4

(ii) Corbula basteroti Hoernes. (x3) Section 33

b Percentage distribution in sections of Capsa lacunosa



c Clay pellet and cobble conglomerates rich in moulds of Corbula basteroti in alternating sandy limestone and calcareous shale.

Section 32



Figure 2.12

Aloididae

Corbula basteroti Hoernes (figure 2. 12a (ii))

Mode of occurrence: This species is most commonly present crowding calcareous sandstone beds to the exclusion of nearly all other fossils. (figure 2. 12c). It also occurs as articulated moulds in lime mud conglomerates in calcareous sandstones (8%), where it has been recycled from mud flats. Articulated specimens occur in 44% of cases.

Geographic distribution: It is rarely present in the northern sections (near the bases of the Zaggut sections and the tops of the Marada sections), but is abundant in the calcareous sandstones of the Jebel Zelten.

Ecology: C. basteroti has no living relatives but the distribution and mode of occurrence suggest a restricted environment:- in this case a sandy substrate in brackish waters. Many of the beds in which it is abundant clearly have the geometry of minor channels.

Boring Bivalves

These are represented by 7 species belonging to 4 families:-

Mytilidae:- * Lithophaga lithophagus Linnaeus:- common (living: tropical and Mediterranean.)

Gastrochaenidae:- * Gastrochaena dubia? (Pennant):- (living, temperate, Mediterranean & subtropical)

Gastrochaena squamulosa Desio (figure 2. 13a (i)(ii))

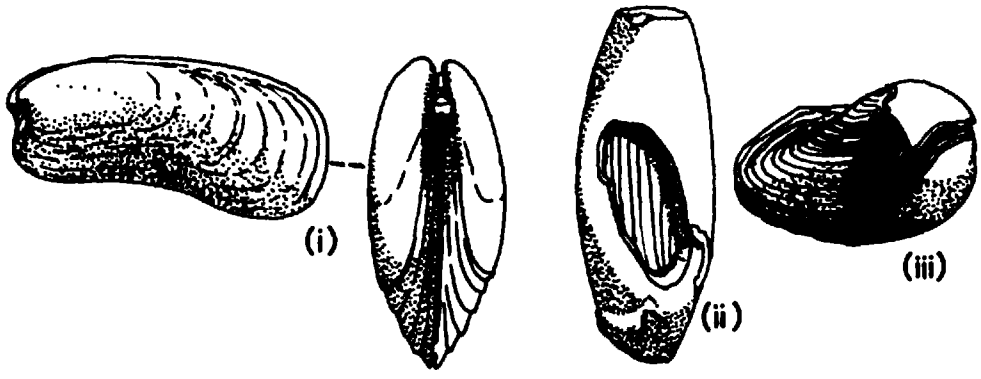
Pholadidae:- Pholas dujardini Mayer (figure 2. 14a (i))

Aspidopholas rugosa Brocchi (figure 2. 13a (iii))

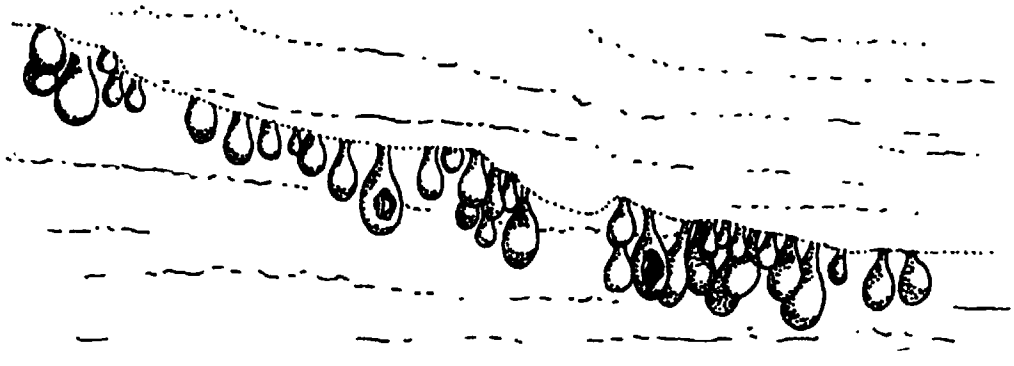
Jouannetia semicaudata Desmoulins

Teredinidae:- Teredo sp. (figure 2. 13c)

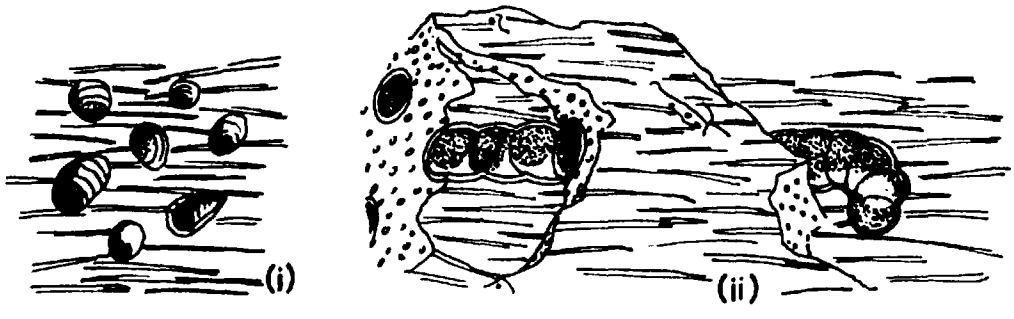
Mode of occurrence: Boring bivalves are nearly always represented by sand or silt filled flask-shaped cavities 5 cm long in cobbles and pebbles in lime mud and clay pellet conglomerates. The shells are rarely preserved, the flask usually being filled with coarse unconsolidated sand.



a (i) Gastrochaena squamulosa Desio (x1) Section 22.
(ii) G. squamulosa (x1) in its flask. Section 22.
(iii) Aspidopholas rugosa Brocchi (x1) Section 22.



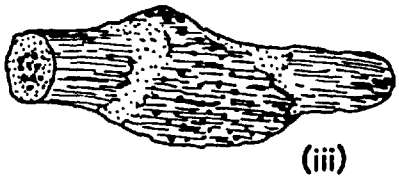
b Horizon in calcisiltite bored by G. squamulosa. Vertical section x0·25 Section 22.



c Teredinid borings in silicified palm wood. Section 30.

(i) 0·35 to 0·55 cm diameter borings (x1)

(ii) Long straight borings with slight constrictions. (x0·5)



(iii) Partly eroded palm trunk with radial (i) borings and longitudinal (ii) borings.

Figure 2.13

Some of the more rounded pebbles are bored on both surfaces (photo 2. 5b) while large horizontal slightly rounded slabs 50 cm long and 10 cm thick, are bored only on the upper surfaces. Highly concentrated boring is present in some pebbles. Short, flasks of Gastrochaena squamulosa are the most widespread (figure 2. 13a(ii)) larger more cylindrical types are caused by lithophaga.

In an exposure of limestone boulders on the flank of a channel at section 5, G. squamulosa borings affect one boulder on two sides. Here 1·0 - 4·0 cm long shells occur in their flasks 2·5 cm from the surface. Very high energy conditions are indicated by their presence on both of the lower surfaces (figure 5. 1).

At Jebel Auf and at the top of section 4, horizons in calcisiltites are extensively Gastrochaena bored marking horizons of early substrate lithification. High concentrations of flasks of all sizes in isolated clumps 30 cm long occur at one horizon. Occasionally beds 5 cm thick composed of flasks are built up. (figure 2. 13b).

Aspidopholas, Jouannetia and Teredo were not found in situ and were probably reworked or bored in wood. Borings occur in silicified palm wood in fluvatile sands at section 30. The most common type bores radially inwards from all around the trunk to a depth of 2 cm. The 0·35 - 0·55 cm diam. tubes have a 0·1 cm annulated case of silica and are generally straight with rounded ends (figure 2. 13c (i)), less common, but longer 10 cm straight silica cased tubes constricted every centi - metre occur at the centre of large trunks and follow the length of the tree only. They often have a sharp geniculation at the internal end (figure 2. 13c (ii)). These borings were possibly caused by teredinids (figure 2. 13c (iii)). Pholas dujardini occurs as redeposited lime mud moulds in calcareous sandstone. It is always articulated but broken and worn.

Geographic distribution: Boring bivalves occur in the upper parts of the Marada sections near the bottoms of the Zaggut sections and throughout the Zelten sections. They occur also in the calcareous sandstones of the Jebel Zelten.

Ecology: All species are intertidal and shallow water marine. Teredo and Jouannetia typically bore into wood or soft sediment. The presence of the former in fluviatile sands indicates that tidal conditions prevailed. Pholas and Gastrochaena bore into soft or hard substrates (e.g. mud, peat, sand, boulders, shells) from low tide to a few metres, while lithophaga prefers a hard substrate (which it excavates by chemical action) in the same depth range. They indicate periods of non-deposition when erosion of clay horizons took place.

Smooth Bivalves

This group comprises a number of species belonging to 17 families. None occurs in such quantity as to make it worth while considering it apart, especially as most occur in bivalve-rich beds. They are tabulated here with ecological notes where available.

Nuculidae:- Nucula placentina Lamarck

Glycimeridae:- ⁂ Pectunculus (Axinaea) cor Lamarck (living, Mediterranean and east Atlantic).

Arcidae:- ⁂ Arca noe Linnaeus: ɑémnoɲ (living, Mediterranean and east Atlantic. Rhone:- gravel 0 - 10 metres).

⁂ Arca diluvii Lamarck: (living, Mediterranean 30 - 60 m. Terrigenous sand biocoenosis of Infralittoral).

Arca turonica Dujardin:

Barbatia sub-helblingi (D'Orbigny)

Limidae:- ⁂ Lima hians (Gmelin): (living, temperate to tropical. Bysally attached or free 0 - 100 m. esp. 10 metres.)

Mytilidae:- Modiolaria sacyi Cossmann and Peyrot:

Modiolaria tenuiradiata Cossmann and Peyrot:

Thracidae:- Thracia (Cyathodonta) dolfussi Cossmann and Peyrot:

* Thracia pubescens (Montagu): (living. subtropical to tropical, low tide to shallow water).

Crassateliidae:- Crassatella raulini Cossmann and Peyrot:

Chamidae:- * Chama gryphoides Linnacus: (living, Mediterranean and east Atlantic. Rhone: beach and shelf to 10 metres).

Lucinidae:- Lucina multilamellata Deshayes: (figure 2. 14b (ii))

Lucina dujardini Deshayes:

Lucina incrassata Dubois de Montpéreux:

* Lucina columbella Lamarck: (living, east Atlantic)

Divaricella ornata Agassiz:

* Jagonia reticulata Sacco (common) (living, temperate to tropical; Rhone: beach
Phacoides broealis Linnaeus: 0 - 5 metres)

Eomiltha callipteryx (Tournouer)

Ungulinidae:- * Diplodonta rotundata (Montagu): (living, Mediterranean and east Atlantic. muddy sand 8 - 65 metres)

Veneridae:- * Venus casina Linneus mut Asthena Dollfuss and Dautzenberg (living tropical and sub - tropical 8 - 70 metres)

Venus burdigalensis Mayer:

* Callista chione (Linnaeus) (living, Mediterranean and east Atlantic: clean sand 0 - 30 m. (esp. 0 - 10 m.) (figure 2. 14a(i))

Meretrix erycinoides Lamarck:

* Chione multilamella (Lamarck) (living Mediterranean)

* Dosinia lupinus (Linnaeus) (living temperate to tropical 0 - 50m, various substrates).

Clementia ungeri Rolle: (figure 2. 14a (iii))

* Tapes deshayesi Benoist: (living, Mediterranean)

Tapes vetulus (Basterot): (some living species of Tapes can tolerate low salinities).

Tellinidae:- * Tellina planata (Linnaeus): (living Mediterranean and east Atlantic)

Tellina ventricosa (de Serres):

* Tellina serrata Renier: (living Mediterranean and east Atlantic)

Arcopagia subelegans d'Orbigny

Arcopagia laminifera Cossmann and Peyrot.

Garidae:- Psammobia affinis Dujardin:

Psammobia uniradiata (Brocchi)

Psammosolen sp.

Solenidae:- Solen siliquarius Deshayes: (figure 2. 14b (i))

Solenocurtus basteroti (Desmoulins)

Mactridae:- Spisula subtruncata (Da Costa) (living, temperate to tropical, low tide to 30m)

Mactra kunstleri Cossmann and Peyrot:

Mactra oblonga Millet:

Aloididae:- * Corbula gibba (Olivi): (living temperate to tropical, low tide - 100m).

Myidae:- Tugonia ornata (Basterot):

The most common species are Arca turonica, Ohama gryphoides, Callista chione, Dosinia lupinus, Clementia ungeri and Spisula subtruncata.

Mode of occurrence: Moulds of smooth bivalves occur in 164 units, typically well preserved in fine limestones and calcareous sands and shales but fragmented in coarse limestones and calcareous sandstones. Beds rich in a variety of smooth bivalves are widespread and usually contain about six species. A few are in life position: e.g. large Venerids at 22, Solenids at section 27 (figure 2. 14b(ii)), where umbones are downward pointing 30 - 45° to the vertical. In 11.8% of the occurrences specimens are still articulated, while recycled moulds in lime mud con - glomerates total 8%.

Geographic distribution: Smooth bivalves are very widespread throughout the Marada, Zaggut and Zelten sections, and in calcareous

sandstones in the Jebel Zelten.

Ecology: The smooth bivalves are all burrowers (from the partially buried Arca to the deep Mya), generally indicating a soft depositional substrate, with or without current activity. There is little sign of tolerance of brackish waters, most still being living Mediterranean and east Atlantic marine species, or having close relatives that are.

From a consideration of all data relating to the ecology, these species may be grouped into four environmental groups.

A) Rather low energy: silts and clays and illsorted sands.

(i) Intertidal and below: Jagonia reticulata, Thracia pubescens, Divaricella ornata.

(ii) Exclusively below: Lucina spp., Venus casina, Dosinia lupinus.

B) Rather high energy: gravels, sands, muddy sand.

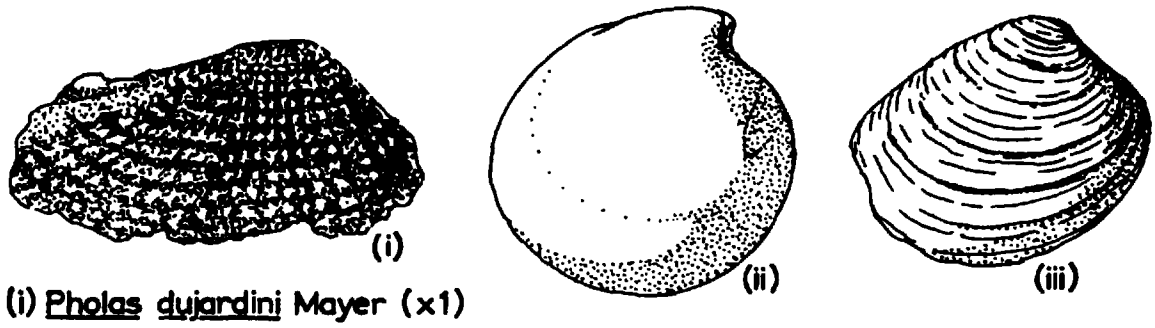
(i) Intertidal and below: Lima hians, Thracia sp., Lucina dujardini, Diplodonta rotundata, Jagonia reticulata, Meretrix erycinoides, Clementia ungeri, Chama gryphoides, Modiolaria sp., Solen sp., Arca noe.

(ii) Exclusively below: Pectunculus cor, Venus casina, Callista chione, Dosinia lupinus, Tapes sp., Tellina planata, Psammobia spp., Spisula subtruncata, Mactra sp., Arcopagia laminifera, Arca diluvii, Corbula gibba, Tellina serrata, Solecurtus, Arca diluvii.

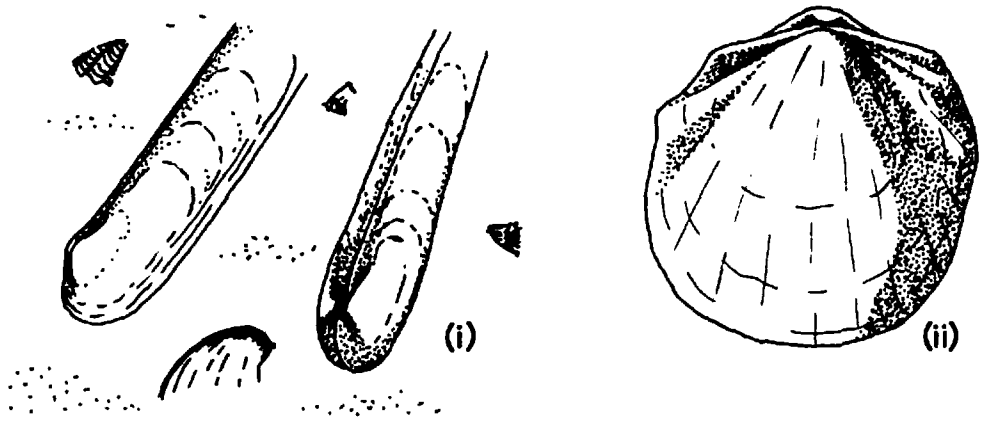
Cephalopoda

Aturia sp.

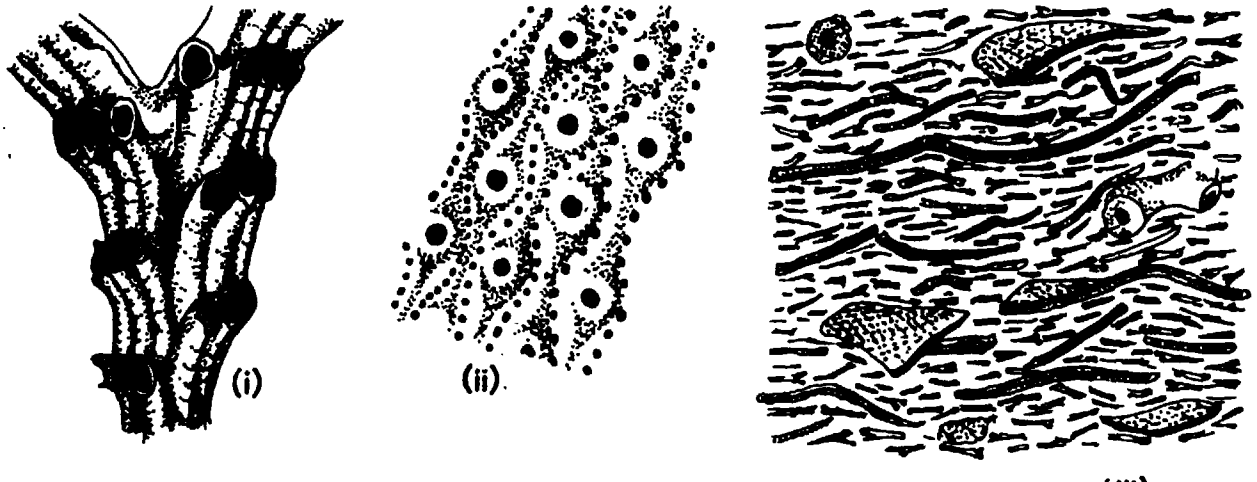
Occurs once only, in the bivalve-gastropod biofacies. Swimming nekton.



a (i) Pholas dujardini Mayer (x1)
(ii) Callista chione (Linnaeus) (x1)
(iii) Clementia ungeri Rolle (x1)



b (i) Solen siliquarius Deshayes in life position. Section 27. (x0·5)
(ii) Lucina multilamellata Deshayes (x1·5)



c (i) Idmonea atlantica Johnston (x50) Section 6
(ii) Trigonopora moniliferum (Milne-Edwards). (x50) Section 17
(iii) Silt horizon crowded with Idmonea fenestrata Busk and with Trigonopora moniliferum following the ripple bedding. (x1) Section 17

Figure 2.14

Bryozoa

The Tertiary bryozoa of Cyrenaica were described by Cippola (1929).

In 1936 Stach attempted a correlation of zoarial form with habitat. In a paper published that year and in one published a year later he divided the cheilostomes into a number of zoarial types indicating part - icular environments. Lagaaij and Gauthier (1965) modified Stach's groups when describing the Recent bryozoan fauna of the Rhône Delta, but were impressed by its application. The following divisions are a slight modification of the groupings of both Stach (1936, 1937) and Lagaaij and Gauthier (1965), and include only those divisions present in the area.

A) Stable forms These types cannot adapt their shape in different environments. They are essentially typical of depths of 30 to 60 metres.

i) Cellariform: These grow around the stems of algae at a variety of depths less than 40 metres. They can exist in areas of rapid deposition (Lagaaij and Gauthier 1965).

ii) Petraliform: These are unilaminate and are attached by radicles to algae, sand or rock in intertidal and subtidal zones.

iii) Reteporiform: These are bilaminate and fenestrate and are restricted to wave zones, especially subtidally where no deposition is taking place. They are common at depths of 30 metres.

iv) Adeoniform: Bilaminate and fenestrate zooaria of this group are flattened and are restricted to depths of 40 to 50 metres.

v) Celleporiform: Massive encrusting Celleporiform types are usually restricted to an algal substrate in areas of slow or non - deposition. They may be intertidal or subtidal.

B) Unstable forms Unstable forms can modify their form depending upon the environmental conditions. Thus a form that is Eschariform in deeper water may become Membramporiform in shallower water.

i) Eschariform: These types are erect and bilaminate. They occur in relatively deep but current affected waters. A few Eschari - form types are stable.

ii) Membraniporiform: Membraniporiform zoaria encrust algae or rocks in intertidal and subtidal zones down to a depth of 20 to 30 metres. They are unimportant in deep water.

Lagaaij and Gauthier (1965) noted that bryozoa were largely absent from areas of rapid deposition, and that with the exception of a few Membraniporiform types, they were stenohaline.

Idmonea spp: (Cyclostomata,Tubuliporidae)

Comprise three species:-

* Idmonea atlantica Johnston (figure 2. 14c(i))

Idmonea fenestrata Busk (figure 2. 14c (iii))

Idmonea disticha Reuss

Mode of occurrence: Short, unworn inter nodes of the branching zoarium 0.5 to I.0cm long, lie parallel to the bedding. They are often associated with Trigonopora moniliferum, crowding the bedding to the exclusion of everything else.

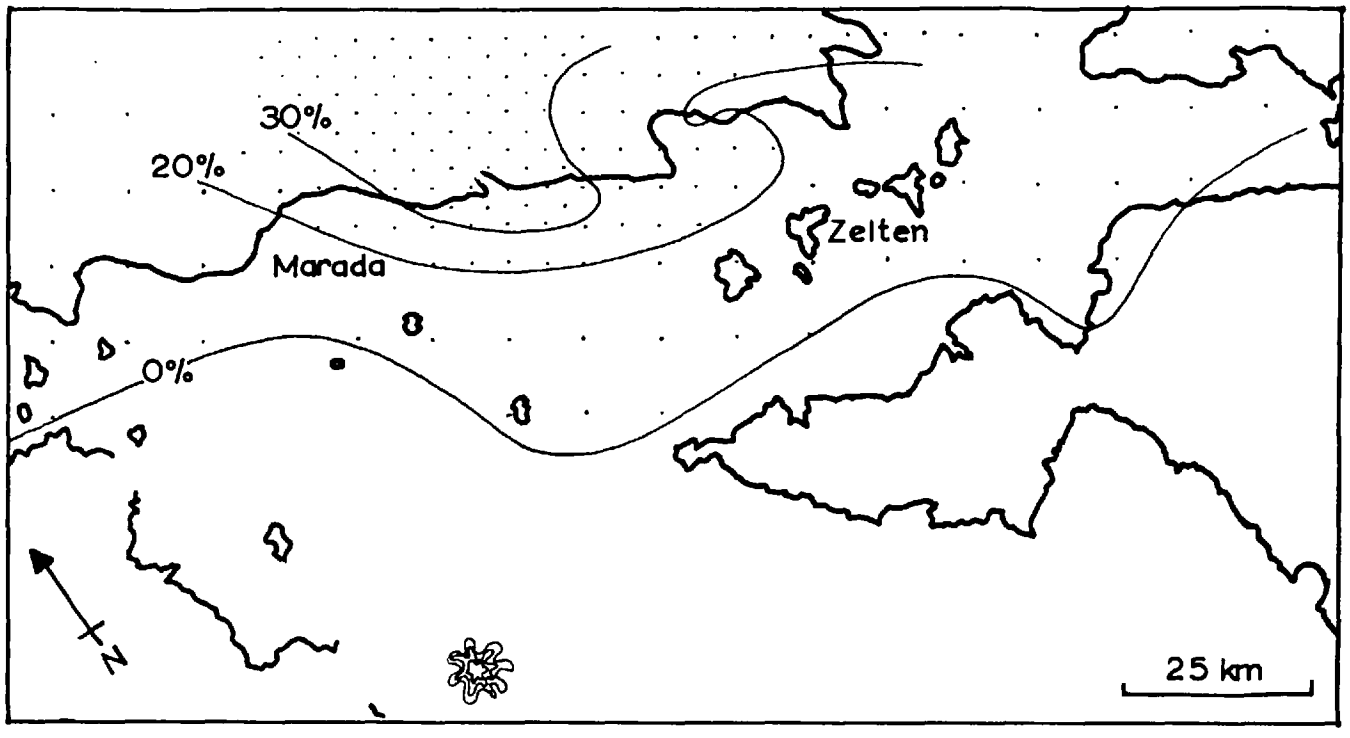
Geographic distribution: I. disticha and I atlantica are common in a richly fossiliferous limestone bed near the bottom of the Zaggut and one of the Zelten sections, forming a good marker band. I.fenestrata crowds the bedding of a single argillaceous limestone or calcareous shale unit one metre thick near the middle of many of the Zelten sec - tions. This is also an excellent marker band, generally about two metres below a bed rich in Echinolampas (figure 2. 14c (ii)).

A limestone bed near the middle of section 25 possibly contains Idmonea, but the preservation is too poor to be sure.

Ecology: Idmonea atlantica is a living species, cosmopolitan in open seas from 18 to 372 metres. Off the Rhône delta it is absent from

a

Percentage distribution in sections of spherical calcareous algae



b

Percentage distribution in sections of bone

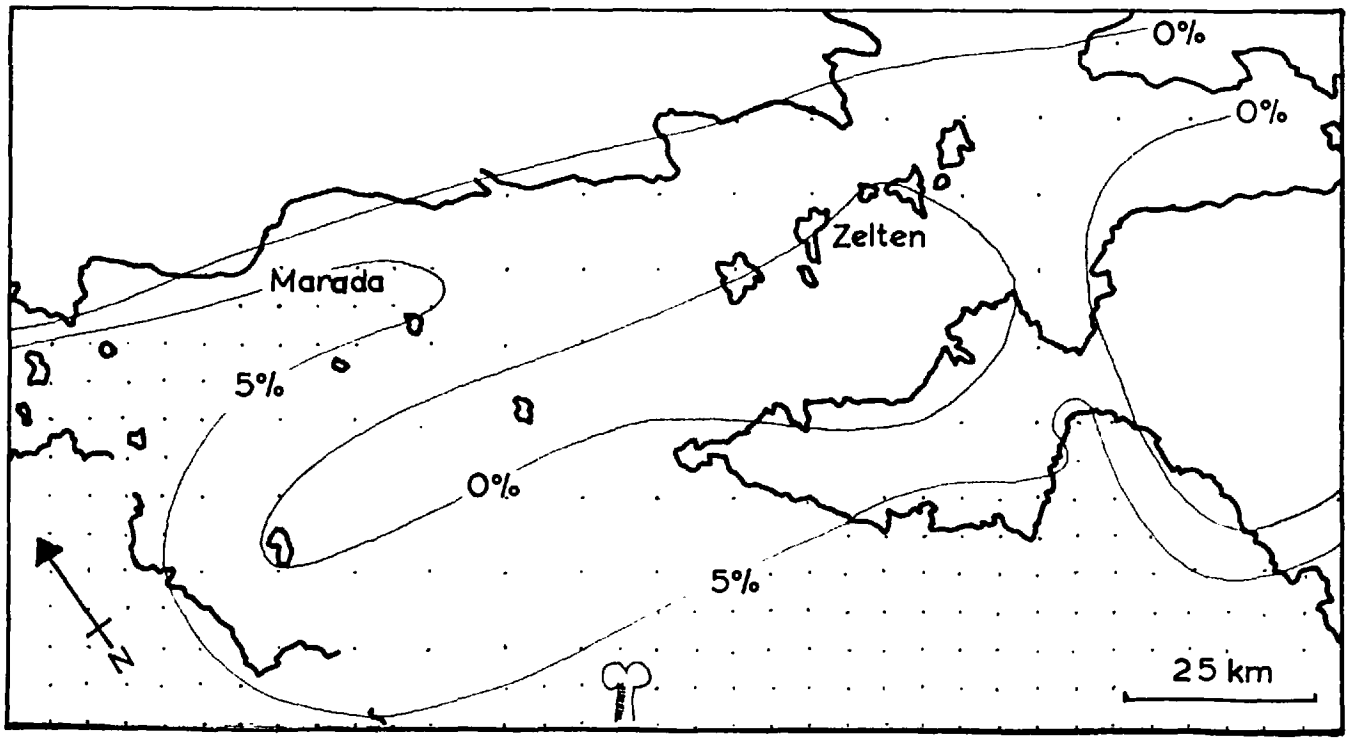
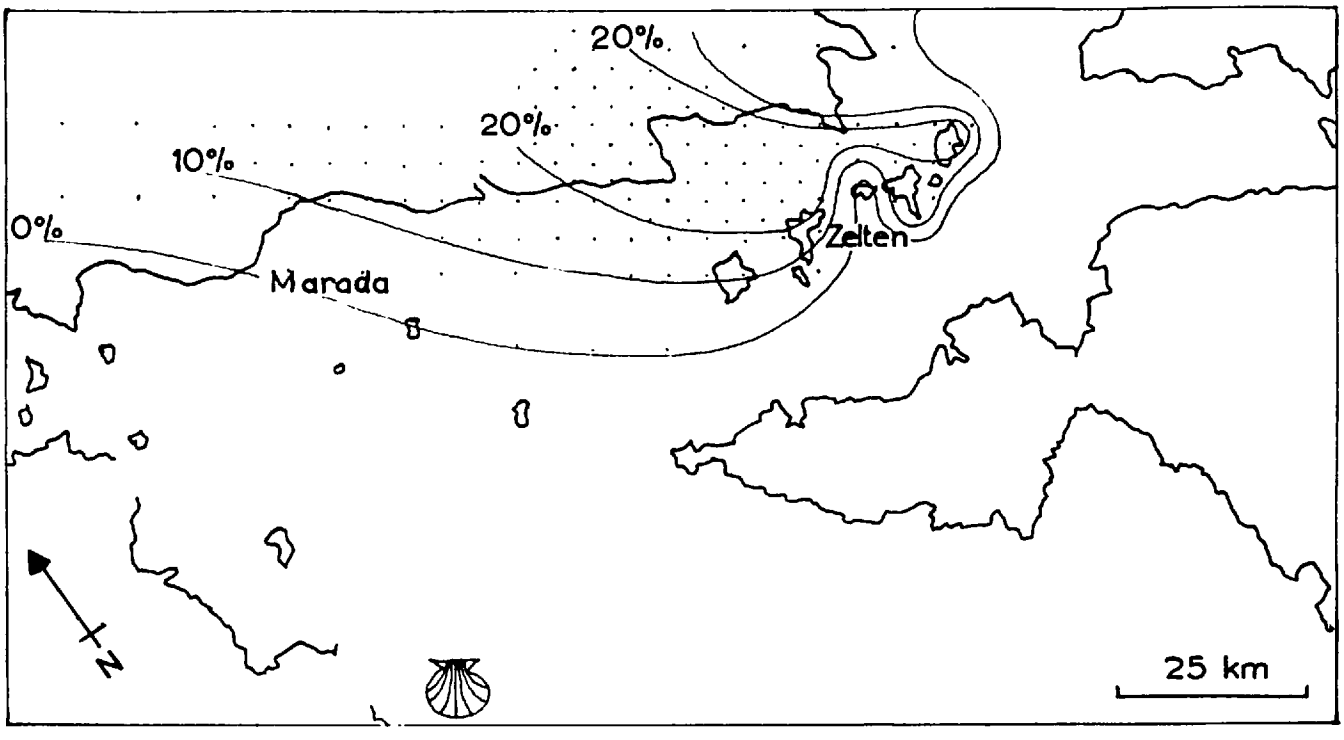


Figure 2.15

a

Percentage distribution in sections of Pecten and Flabellipecten



b

Percentage distribution in sections of Chlamys

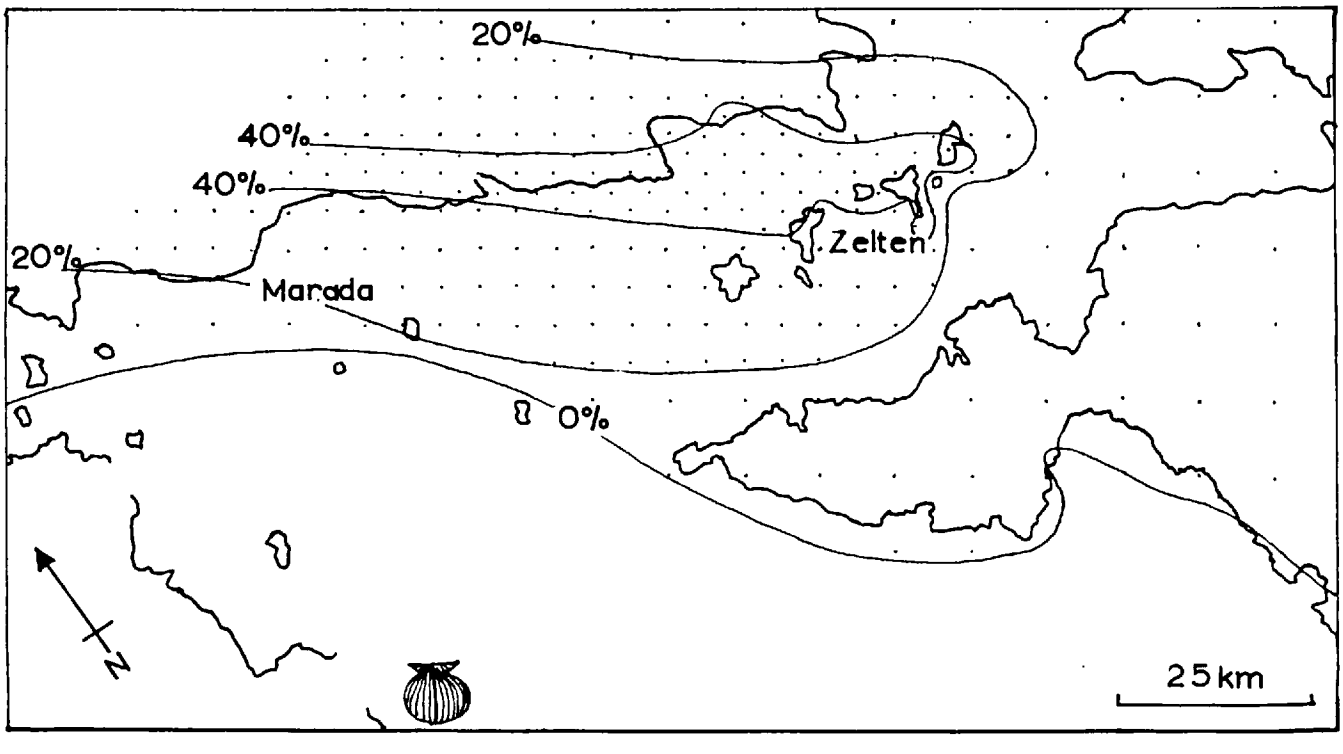
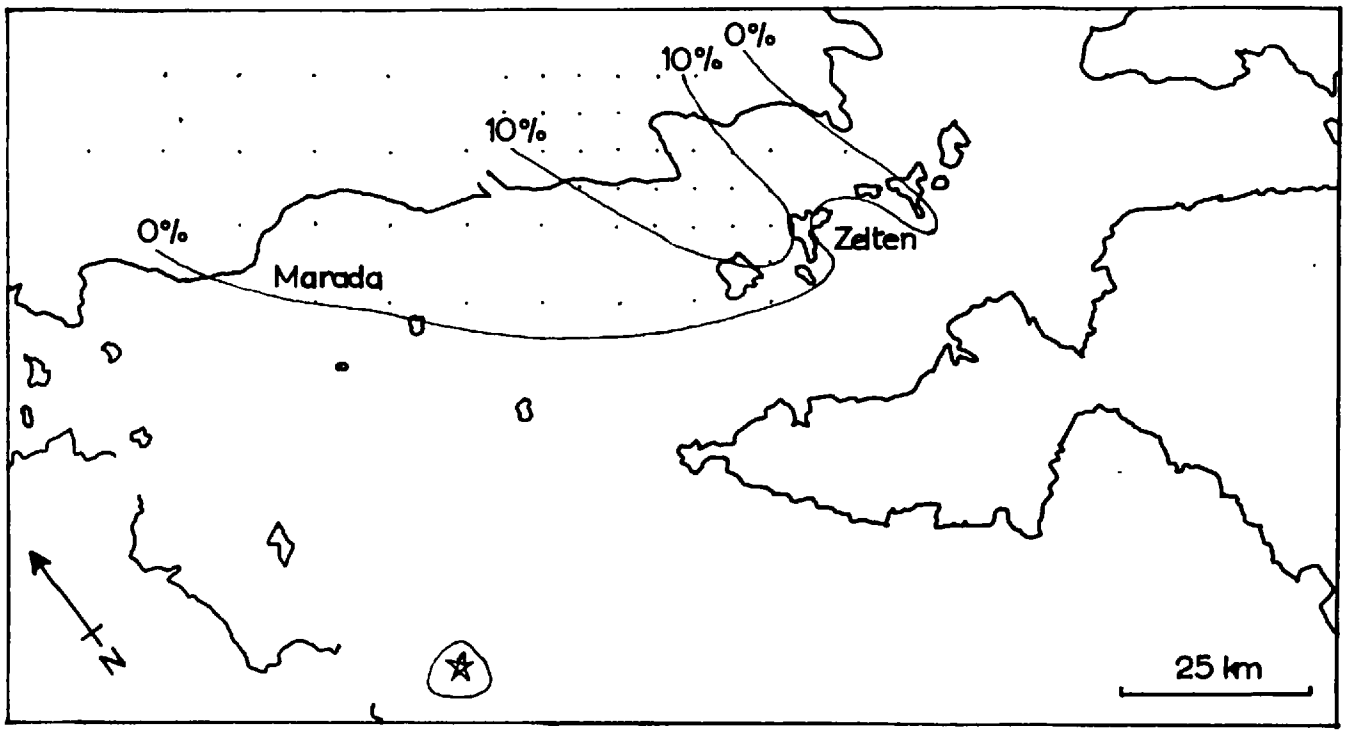


Figure 2.16

a

Percentage distribution in sections of Scutellids without lunules



b

Percentage distribution in sections of Scutellids with lunules

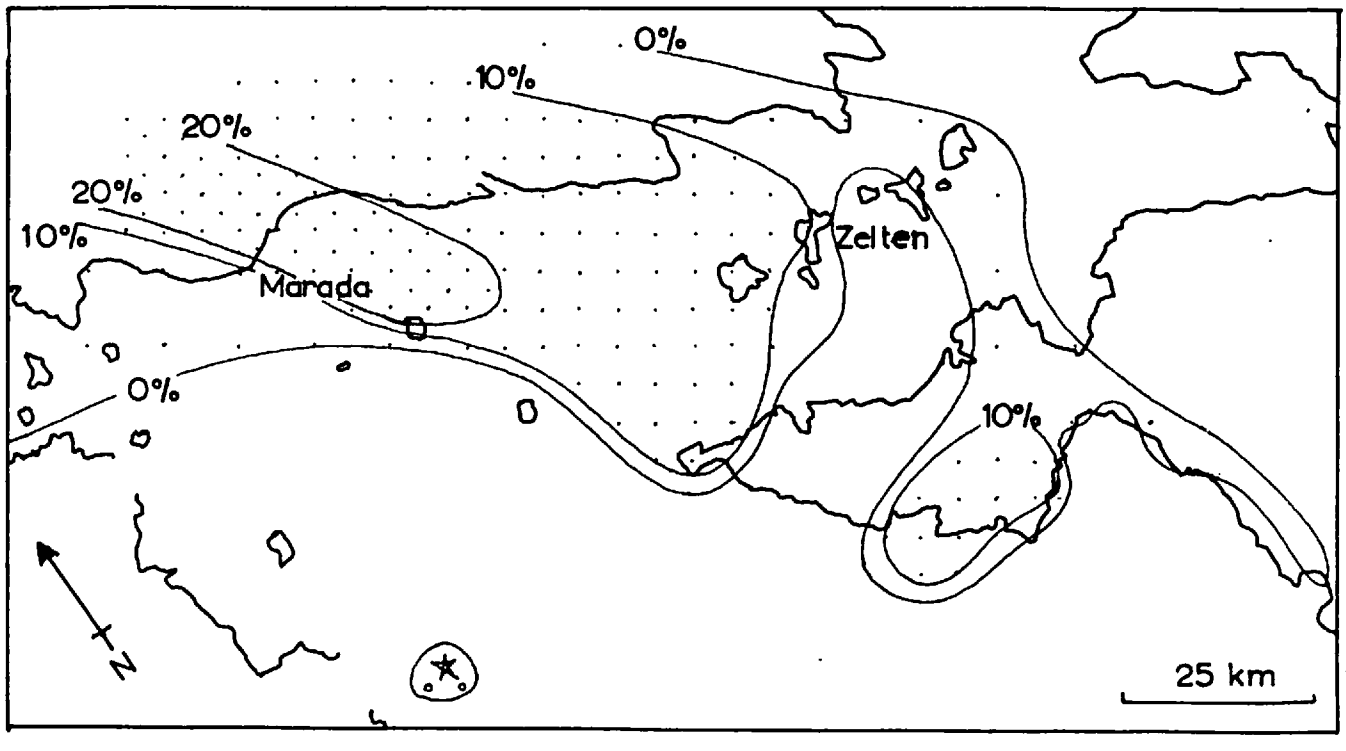


Figure 2.17

the top 40 metres (Lagaaij and Gauthier 1965).

Trigonopora moniliferum (Milne-Edwards) (Ascophora, Adeonidae) (fig.2.14c(ii))

Mode of occurrence: This occurs in beds as up to 1·0 cm long unworn fragments of the original erect bilaminate fenestrate zooarium or as broad flat sheets up to 1.5 cm long parallel to the bedding. Where it is abundant the fragments follow the horizontal bedding or the rippling demonstrating the originally flexible nature of the calcified zooarium (figure 2. 14c (iii)). Rigid examples are generally thicker and demonstrate 2^{o} calcification.

Geographic distribution: T. moniliferum is the most common fossil in the Zelten area occurring in 290 units. Where abundant, 500 fragments may occur in a square metre. It is present throughout the Zaggut and Zelten sections, is scattered in the Marada sections and in the calcareous sandstones and limestones of the Jebel Zelten.

Ecology: T. moniliferum is a living Adeoniform species, present in fully saline open seas of the Mediterranean Circalittoral and the Posidonia lawns of the Infralittoral. In the Rhône area Adeoniform types are only present on non-depositional bottoms in 40 - 50 metres of water.

Holoporella desioi Cippola (Ascophora, Celleporidae) (figure 2. 18(a))

Mode of occurrence: H. desioi occurs as broken branched and unbranched cylinders 2·0 - 3·0 cm long lying parallel to the bedding. Slightly broken larger branching complexes indicate that the zoarium was a large ramose structure with numerous radiating subhorizontal branches arising from a massive vertically disposed centre. Frequently the core of an arm is filled with sediment (representing soft algae) illustrating the encrusting habit of this species. Occasionally the colony is cone-shaped with a flat, or slightly concave base 2·0 - 5·0 cm

diameter and a height of 2·5 - 3·0 cm. These types probably encrusted algae in the intertidal zone because they are always present in presumed intertidal occurrences of Holoporella desioi.

The range of types is as follows:-

Cylindrical by self	87·3%
Cone-shaped by self	5·3%
Cylindrical + Cone-shaped	7·4. (14 units of which 80% are limestone)

Geographic distribution: Occurrences are scattered at the tops of the Marada sections, but it is found throughout the Zaggut and Zelten sections and in the calcareous sandstones of the Jebel Zelten.

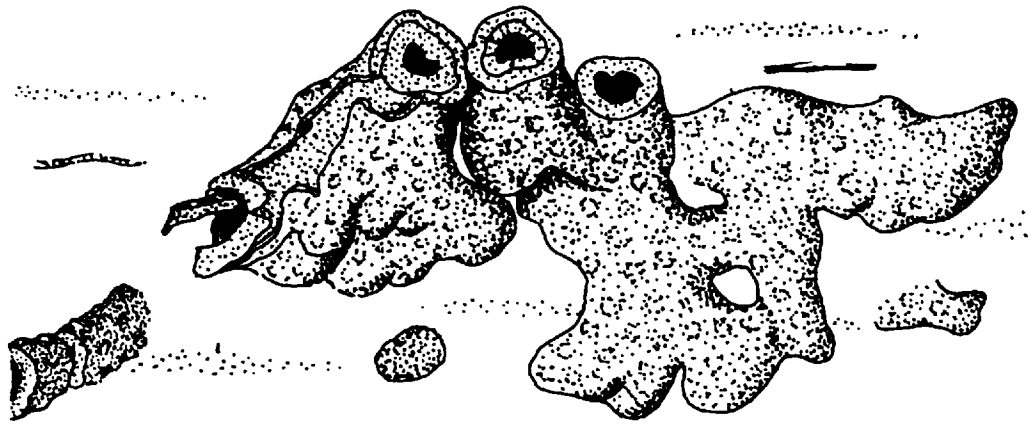
Ecology: Celleporiform Bryozoa are typical of algae substrates in intertidal and subtidal zones. They indicate normal salinity, wave zones and non-depositon. In the slightly brackish waters off the mouth of the Rhône there is a great reduction in the population of Cellepora pumicosa , though it is abundant on sandy marls elsewhere at 20 - 30 m. Throughout the Mediterranean it is common between 40 - 60 metres.

* Retepora cellulosa Linnaeus (Ascophora, Reteporidae)

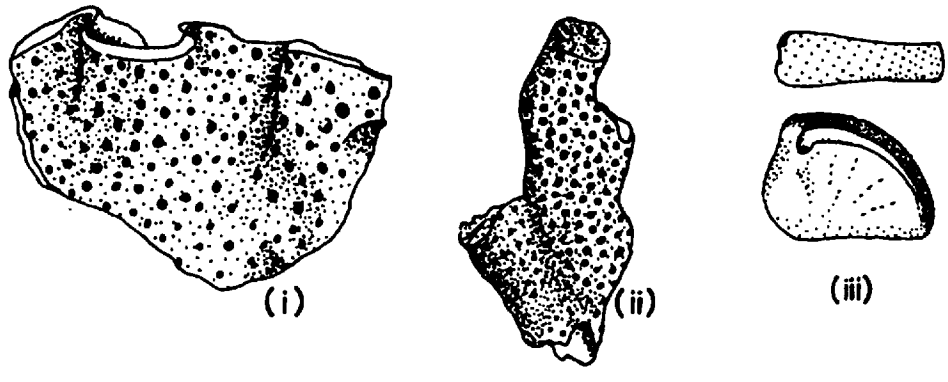
Mode of occurrence: This species occurs as fragmentary skeletons 1·0 to 3·0 cm diameter and is nearly always rare.

Geographic distribution: It is present only towards the bottoms of the Zaggut and Zelten sections.

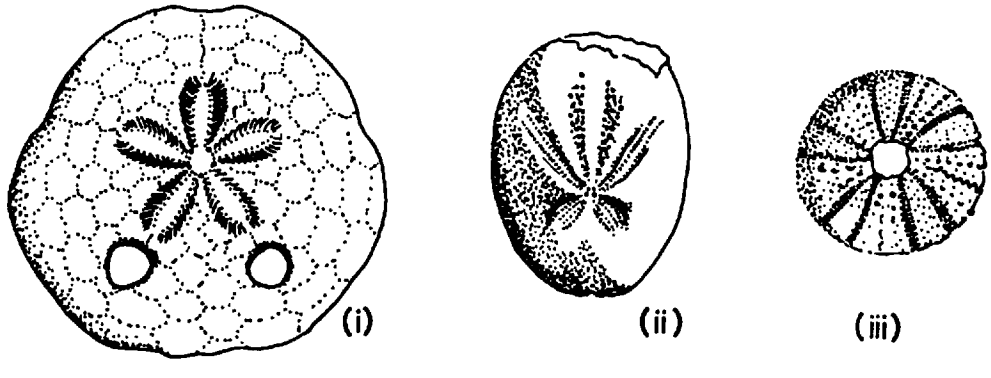
Ecology: R. cellulosa is a stenohaline species living in the Atlantic and Mediterranean in areas of slow or non-deposition affected by gentle currents. It is especially common at 30 metres depth but may occur between 5 and 100 metres.



a Holoporella desioi Cippola in calcarenite. (x1) Section 17



b (i) Holoporella fabianii Cippola. (x1) Section 23
(ii) H. fabianii. (x1) Section 5
(iii) Asteroid plate. (x2) Section 5



c (i) Amphiope arcuata Fuchs. (x1) Section 10
(ii) Agassizia cyrenaica Desio. (x1) Section 14
(iii) Psammechinus dainelli Desio. (x1)

Figure 2.18

Other Bryozoa:

These probably occur quite frequently but were only identified as rare examples in samples so their distribution does not affect the environmental reconstruction. They are listed with the biofacies in which they occur. They are all typical of shallow warm waters and are largely stenohaline.

Cyclostomata: Entalophoridae

Microecia suborbicularis (Hincks): This was found once. (Lopha biofacies)

Ecology: A living cosmopolitan species found from 4 to 10 metres in the Mediterranean.

Tretocycloeciidae

Tretocycloecia dichotoma Reuss: Occurs in one unit (Crassostrea biofacies).

Malacostega: Electridae

Electra elliptica Reuss: This occurs quite commonly and is Membraniporiform, (Crassostrea biofacies).

Mode of occurrence: It typically encrusts Crassostrea gryphoides and Placenta miocenica in Zoaria 5·0 cm diameter.

Ecology: The genus is common today in slightly brackish waters off the mouths of rivers in 0 - 30 metres water.

Hincksinidae

Vibracellina cremai Cippola

This occurs once (Trigonopora biofacies)

Coilostega: Calpensiidae

Calpensia impressa (Moll): This occurs once (spherical calcareous algae biofacies.) It is Membraniporiform, living in the Mediterranean and Atlantic from 25 - 30 metres (rarely down to 100m).

Pseudostega: Cellariidae

Cellaria farcimioides (Johnston): This occurs once (mixed oyster and bivalve-gastropod biofacies). Cellariform.

*Tubucellaria cereoides (Ellis and Solander): This is found in the Idmonea biofacies.

Ecology: It is a living species found in warm oceans.

Ascophora: Celleporidae

Holoporella fabianii Cippola: Occurs twice in the Echinolampas biofacies, forming a horizon for correlating between sections 5 (figure 2. 18b (ii) and 23 (figure 2. 18b(ii)).

Ascophora: Exochellidae

*Bathocella canui Cippola: This occurs once (Trigonopora biofacies).

Ecology: It is a living Eschariform species attached to sandy bottoms near 20 metres depth.

Ascophora: Mucronellidae

Porella conferta (Reuss): This occurs twice in the Idmonea biofacies. It is Eschariform.

Porella cervicornis (Pallas): This is found once in the Vermetus biofacies.

Ecology: It is Eschariform, living in the Mediterranean (40 - 80 m) on the hard substrates of the sublittoral, and in the Atlantic in 140 - 180 m.

Smittina regularis (Reuss): This occurs once in the Placenta biofacies. It is Eschariform.

*Hippopodina campanulata Cippola: This occurs once, in the Crassostrea biofacies. It is Petraliform.

Ascophora: Schizoporellidae

Escharina (Schizolavella) africana (Canu): This occurs in the smooth bivalve biofacies. It is Membraniporiform.

Schizomavella escharoides Cippola: This is found in the Vermetus biofacies. It is Membraniporiform.

Geographic distribution: These Bryozoa occur near the bottoms of the Zaggut sections and throughout the Zelten sections and are rare to the south.

ECHINODERMA

Asteroid Plates (figure 2. 18b (iii))

Mode of occurrence: Smooth triangular separate marginal arm ossicles 1·0 cm long are the most common type, though a few central pentagonal forms are present.

Geographic distribution: They occur at the tops of one Marada section, and scattered through the Zaggut and Zelten sections (mainly towards the base of the former and the top of the latter).

Ecology: Living Asteroids are scavenging or carnivorous epibionts, occurring in shallow marine water. They are common in the Posidonia lawns of the Mediterranean Infralittoral.

Regular echinoids

These are represented by :- Psammechinus dainelli Desio (Echinidae)
Cyathocidaris avenionensis (Desmoulins) (Cidaridae)

Mode of occurrence: Psammechinus is preserved as unbroken tests (figure 2. 18c (iii)), while Cyathocidaris is represented only by radioles and crushed tests.

Geographic distribution: Regular echinoids are present at Jebel Auf and are found scattered through the Zaggut and Zelten sections.

Ecology: Living regular echinoids are epibiontic scavengers living on relatively stable substrates where little or no sedimentation is taking place. Species of Psammechinus occur in the Atlantic and Mediterranean. In the latter they occur in depths of 20 - 40 m, in the Posidonia lawns of the Infralittoral.

Scutellids without lunules (Scutellidae)

These comprise three species:-

Scutella checchiae Desio

Scutella stefaninii Desio (photo 2. 6a)

Scutella bricchettii (Desio)

Mode of occurrence: They occur in limestone units lying parallel to the bedding. In section 7 a specimen lying at 90° to the bedding has been broken off at the top by a current from N. 60° E.

Geographic distribution: Scutellids are scattered through the Zaggut sections and near the bottoms of the Zelten sections (fig. 2. 17a).

Ecology: Scutellids are shallow burrowing scavengers in subtidal carbonate sands. They are especially common in warm clear water on shoal banks in 3 - 8 metres of water (down to 20m.) away from algae.

Scutellids with lunules (Astriclypeidae)

These comprise two species:-

Echinodiscus fuchsi (Fourteau) (photo 2. 6b)

Amphiope arcuata Fuchs (figure 2. 18 c (i))

Mode of occurrence: These most frequently occur as broken or fragmentary tests lying parallel to the bedding, or at high angles to it if the rock is bioturbated. At section 23 traces probably caused by E. fuchsi are present (see section on burrows).

Geographic distribution: Occurrences are scattered here and there through the Marada and Zaggut sections, in the lower parts of the Zelten sections and through the calcareous sandstones of the Jebel Zelten. (fig. 2. 17b).



Photo. 2.6. Scutellids.

a. (left) Scutella stefaninii Desio

b. (right) Echinodiscus fuchsi (Fourteau)

Ecology: The ecology is similar to that of the Scutellids without lunules but many living species can withstand the lowered salinities of estuaries and lagoons. The living Astriclypeid Mellita can tolerate 20‰. They can also live in sheltered intertidal environments where they burrow forward in the top centimetre or so of sediment with the posterior exposed.

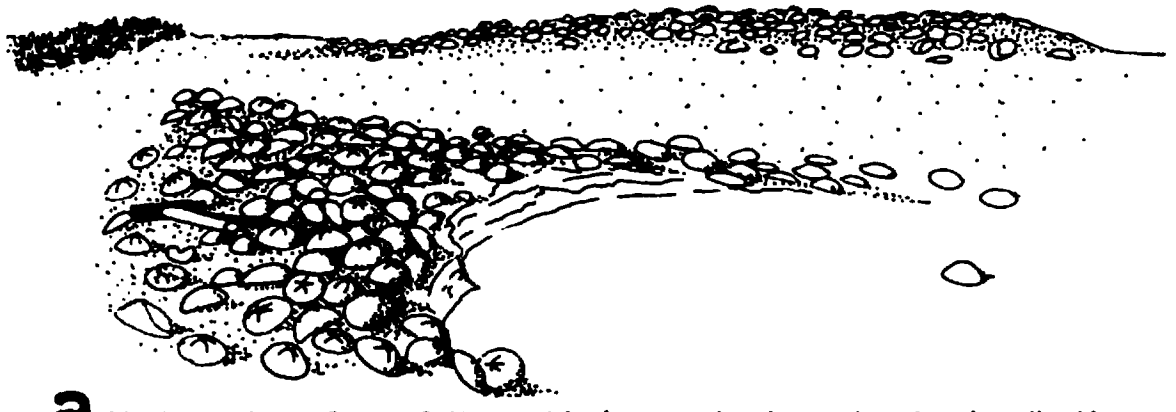
Echinolampas spp. (Echinolampadidae) (figure 2. 19b)

Echinolampas hemisphericus var cyrenaicus Desio

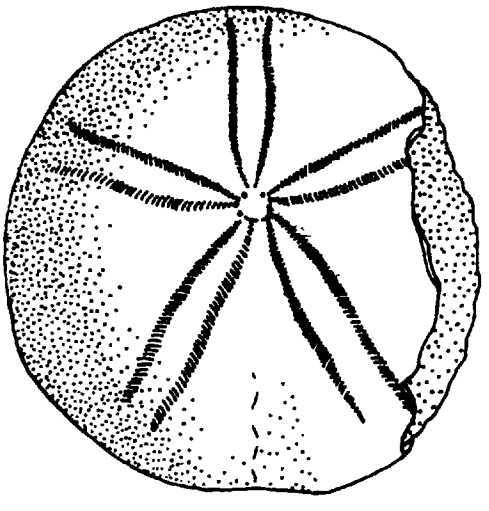
Echinolampas cremai Checchia-Rispoli.

Mode of occurrence: Echinolampas is common in limestone units at one level in the Zaggut and Zelten sections where it forms a good marker horizon. In most beds the specimens are rather jumbled, up to 40% lying on their sides or upside down. In the best exposed outcrop (fig. 2.19a), large numbers of individuals are associated with Lopha plicatula on the top surface of a limestone unit. Specimens occur in clusters (in concentrations of up to 85 per metre^2) measuring 2 x 1·7 x 1·2m. in a matrix of fragments on a level 7 - 8 cms above the general bed surface. There is a marked conformity in the size of specimens: 70% are 9·8 cm long, the range being 5·5 - 11·3 cm. Lopha plicatula is concentrated in similar clusters in the same bed but is exclusive of Echinolampas. Both are very close to their position of life and their exclusiveness illustrates the rapid lateral dying out from complete specimens through fragments to nothing in these limestones. (fig. 2. 19a)

Geographic distribution: They are present in a single bed or group of closely associated beds in the Zelten and Zaggut sections forming a good marker horizon. There are five other scattered occurrences, two of which contain Holoporella fabianii and represent another marker horizon.

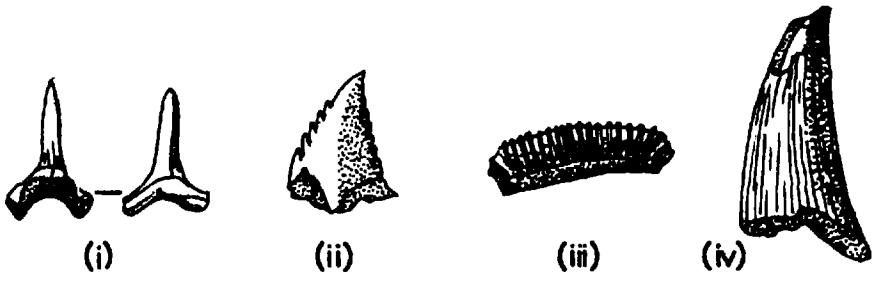


a Horizontal surface of the Echinolampas horizon showing localisation of specimens on slightly elevated areas near Lophg reefs (on left). Hammer is 40cms long. Section 12.



b

Echinolampas sp.
(x0·5) Section 12



(i) (ii) (iii) (iv)

c (i) Odontaspis acutissima Agassiz. (x1) Section 3.
(ii) Hemipristis serra Agassiz. (x1) Section 3.
(iii) Myliobatis sp. (x1) Section 3
(iv) Crocodile tooth. (x1) Section 3.

Figure 2.19

Ecology: The conditions under which species of Echinolampas lived were probably similar to those of Lopha plicatula. They probably lived on the low banks associated with reefs of the latter. Species of Echinolampas are stenohaline, scavenging epi- or inbionts found on sandy bottoms deeper than ten metres in the tropics.

Agassizia cyrenaica Desio (Schizasteridae) (figure 2. 18c (ii))

Mode of occurrence: This occurs as crushed or slightly broken specimens in nine limestone units.

Geographic distribution: A. cyrenaica is restricted to a bed near and below the Echinolampas horizon in a few of the Zaggut and Zelten sections. It reaches its greatest concentration at section 14.

Ecology: Agassiza was probably a burrowing scavenger in shallow marine waters.

Other Irregular Echinoids

This group probably comprises several species but only three have been recognised:-

Radiobrissus geneffensis Fourteau (Brissidae)

Brissopsis sp.

Lovenia loveni Checchia - Rispoli (Loveniidae)

Mode of occurrence: These forms usually occur as rare and largely unidentifiable fragments 0.5 cm associated with a wide variety of fossils and rock types.

Geographic distribution: They are scattered through the Zelten and Zaggut sections, and at Jebel Auf.

Ecology: Spatangoids are stenohaline rather deep burrowing scav - engers. They are especially common in densely grassed channels from low tide to 28 metres. They occur on the terrigenous bottoms of the Infra and Circalittoral of the Mediterranean.

Teeth

Squaloidea:- Odontaspis acutissima Agassiz (figure 2. 19c (i))

Carcharodon sp.

Saurocephalus faiumensis Dames.

Sharks fin.

Hypotremata:- Myliobatis sp. (common) (figure 2. 19c (ii))

Pristis sp.

Hemipristis serra Agassiz (figure 2. 19c (ii))

Mode of occurrence: Teeth are typical of clay pellet and lime mud conglomerates in a wide variety of environments where they are associated with bone fragments.

Geographic distribution: They are scattered through the limestones and calcareous sandstones throughout the area.

Bone

This comprises bones of amphibia, birds and mammals. Well preserved specimens of all types have been recognised by Savage from Bristol University, and he and Harris are describing the abundant mammalian fauna.

Mode of occurrence: Most of the bones are unidentifiable worn ffagments 10 cm, occurring in calcareous sandstones and limestones, especially in clay pellet conglomerates and in beds above erosion surfaces. Well preserved specimens in fluviatile sands show that crocodiles (fig. 2. 19 c(iii)), turtles and a wide variety of mammals were present.

Geographic distribution: Bones are present throughout the lower portions of the Marada, Zelten and Zaggut sections, and abundantly in the sands and calcareous sandstones of the Jebel Zelten (fig. 2. 15b).

Ecology: The crocodiles and turtles indicate a river facies of brackish or fresh water while the mammals listed by Savage (in discussion of Selley 1968) indicate a tropical or subtropical savannah climate:- They include:- Carnivora, Creodonts, Proboscidea (Mastodon, Deinotherium),

Perissodactyls (Rhinóceros), Anthracotheres (Hippopotamus), Giraffes, Ruminants, Sirenians, Suids.

The Temperature and Climate indicated by the fossils.

The Aquatic Fossils

Out of a total of 36 species that are still living, six (16%) have tropical or subtropical distributions, the rest are also Temperate (largely Mediterranean). Their detailed distribution is as follows:-

(i) Mediterranean only: 22%

(ii) Mediterranean and Tropical E. Atlantic: 53%

(iii) Atlantic only: 3%

(iv) Indian or Pacific oceans: 7%

(v) Cosmopolitan: 11%

(There was no information on 4%).

These distributions clearly indicate a close relation between the biota and that of the Mediterranean and Tropical East Atlantic.

For a broader picture comparisons were made between the groups not living today and their recent generic or familial relatives. Of 31 groups compared, 49% are tropical or subtropical, the rest are also temperate/mediterranean. In this case a much higher percentage show a tropical or subtropical distribution, so that although most of the living species are still present in the Mediterranean region, the whole biota is much more closely related to the tropical Atlantic. There is relatively little correlation with groups now living in the Pacific and Indian Oceans, and evidently there was little connection in this direction in the Miocene.

The mean surface temperatures of the tropical east Atlantic (and west Atlantic including the Gulf of Mexico) range from 20° - 25° C (January) to 25° - 30° C (July). The corresponding figures for Cyrenaica at the present day are 10° - 15° (January) to 20° - 25° (July).

The Continental Fossils

The continental fauna and flora indicate a tropical savannah type climate. This is a conclusion arrived at independantly by Chiarugi (1929) who examined the silicified wood, and Savage (1965) who examined the Vertebrates.

CHAPTER 3

THE BIOFACIES

Biofacies

The fossils (described in the last chapter) have been classified into a number of recurrent assemblages, defined by the dominance of one or more of the fossil groups. These assemblages have been termed "biofacies" and the environment they represent is limited by the ecology of their most important members. By visual comparison of the lists of groups for each of the units twenty such biofacies were recognised.

For each biofacies tables indicating the list of groups in order of importance and the percentage of units in which each occurs are followed by a biotal analysis. This consists of an analysis of the habits of the various groups and is strictly for comparitive purposes. Because the groups are subjectively delineated the percentage of each feeding habit, for instance, bears no relation to the true representation of that habit by species or numerically - it is merely meant as a guide to illuminate trends between the different biofacies.

The occurrence of the biofacies in the various lithologic types and the number of units affected by bioturbation are also expressed as percentages. The depths given for the biofacies represent the optimum range and may be much more variable.

The compactness of the biofacies and the ease with which most can be referred to a particular environment suggests that most are natural assemblages and there has not been much mixing.

Biofacies 1: (61 units) Trigonopora biofacies

This biofacies is dominated by Trigonopora moniliferum and Holoporella desioi, but includes important pectinids, asteroids and crabs. The

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Photosynthesisers	5		6	7	8	4	6	3		7	6			9	5					30
Herbivores	20		30	29	32	41	30	29	23	29	28	12	37	36	33	23	40	36		40
Carnivores	16		6	4	8	7	12	12	6	7	17	12	12	4	5	19	20	12	100	40
Deposit feeders			2	4	4	4	3	6			8			4	5	14	13	12		
Suspension feeders	61	100	52	63	48	52	50	50	70	56	49	72	50	50	58	48	40	48		
Epibionts	77	88	66	67	64	63	72	71	76	70	54	48	100	59	53	48	46	56	100	
Endobionts	22	12	45	33	44	41	27	30	24	29	40	60		31	48	38	33	24		
Calcite-shelled	72	88	69	60	72	63	63	54	83	74	42	24	50	59	58	28	33	24	100	
Stenohaline	63	12	64	77	72	70	50	42	60	51	31	48	50	45	48	19	20	24		
Bioturbated	36	33	34	33	36	31	46	50	20	44	47	48	62	70	65	81	67	50	90	26

Biotal analysis of the biofacies

ASSOCIATION OF FOSSILS WITH THE BIOFACIES

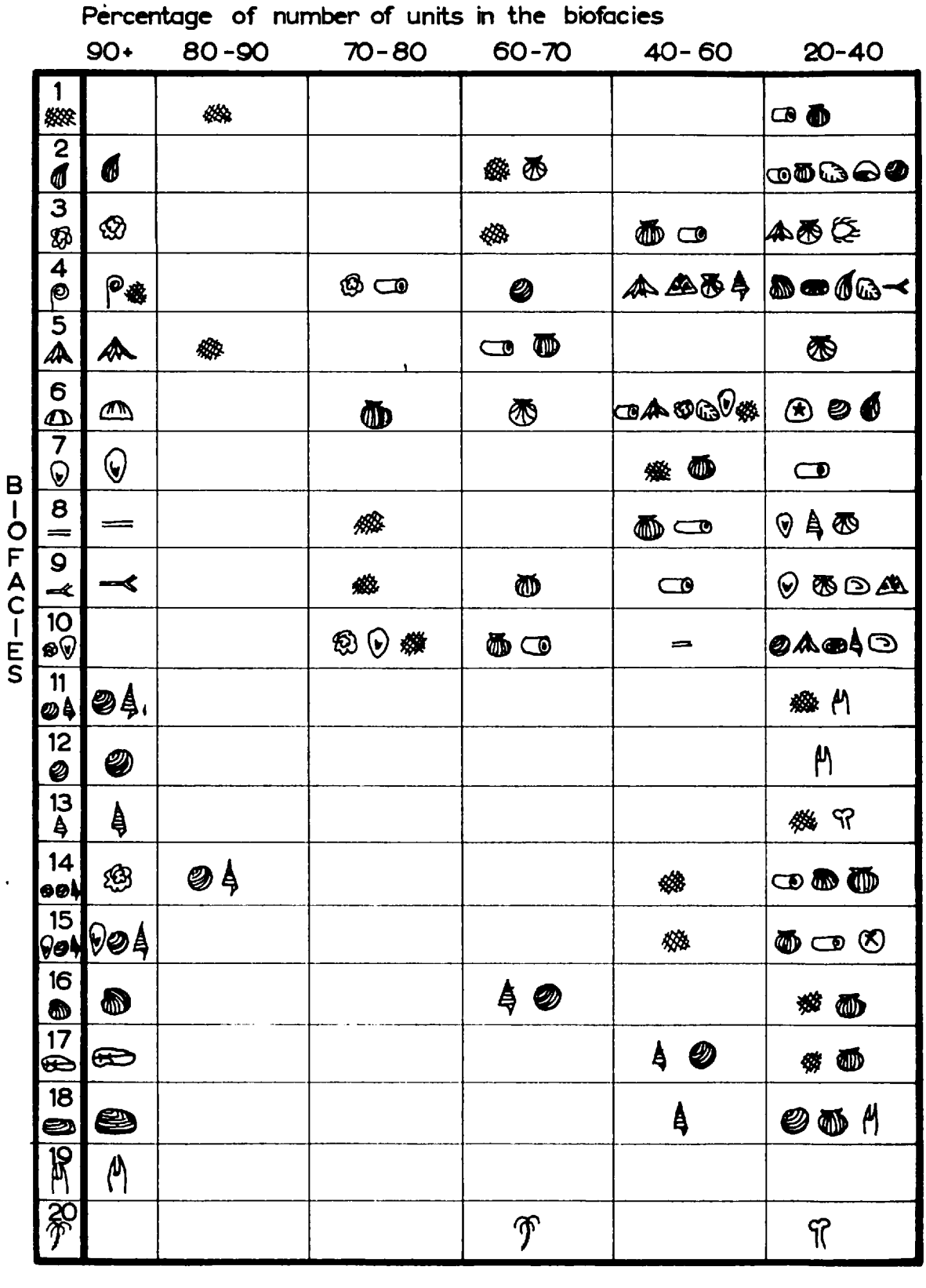


Figure 3.1

groups are overwhelmingly stenohaline suspension-feeding calcite-shelled epifauna, many of them dependant upon or closely associated with sub - marine algae. The biofacies occurs in a variety of sediment types, but mainly in the limestones (74%) and their associated shales (18%). Bioturbation affects 31% of the units.

The environment: represents an algal-rich slow or non-depositional carbonate substrate with gentle to moderate current activity in normal salinity, at 25 - 50 metres. Normal salinity here is considered to be that of the surface of the tropical Atlantic, i.e. 36 - 37°/oo. At the present day off the coast of Cyrenaica the salinity is between 38 and 39°/oo, which probably accounts for the absence of may of the more brackish water tropical groups.

The high percentage of suspension-feeding epibionts indicates that the substrate was either too densely vegetated, too cohesive or not rich enough in organic matter to support most burrowing groups. The only important burrowing forms are scavenging echinoids typical of densely grassed areas and crabs and worms. The present day equivalent in the Mediterranean would be the Posidonia lawns of the Infralittoral.

Biofacies 2 (3 units) subfimbriata biofacies

This is a modification of Biofacies 1, characterised by Ostrea frondosa var subfimbriata, that occurs in three limestone units. All of the groups are suspension-feeders, most are calcite-shelled epifauna and none requires an algal substrate. Half of the groups are to some extent euryhaline, O. frondosa var subfimbriata probably being able to stand 30°/oo.

The environment: Is similar to biofacies 1 but lacks an algal substrate (hence the absence of scavenging burrowers), and is charact - erised by a slightly lowered salinity.

Biofacies 3 (50 units) Spherical calcareous algae biofacies

The characteristics of this biofacies are spherical calcareous algae with a generally diverse biota. Only about half are suspension-feeders, many being herbivores requiring an algal substrate. All of the most important groups are stenohaline epibionts, but many of the less important ones are euryhaline inbionts. Both the spherical coralline algae and Ostrea plicatula prefer soft lime mud substrates in calm waters between 15 and 30 metres. 34% of the units are affected by bioturbation. The biofacies occurs almost exclusively in limestones (86%), and their associated shales (12%).

The environment: represents an algal-rich soft lime mud substrate in fully marine waters between 15 and 30 metres, the rate of deposition being slow but faster than in biofacies 1 and 2 and the energy level lower. The softer substrate is reflected in the presence of inbionts.

Biofacies 4 (9 units) Vermetus biofacies

This is characterised by vermiform gastropods and Trigonopora moniliferum with a diverse biota rather similar to biofacies 3, but with rather more suspension-feeders, and more that are stenohaline.

Vermiform gastropods and burrowing smooth bivalves (present in 66% of units) require rather clear water and gentle to moderate current activity. The substrate is affected by burrowing in 33% of the units and supports a large population of inbionts, so it was soft (as in bio - facies 3). Occurrence of the biofacies is limited to nine limestone units.

The environment: represents an algal-rich soft carbonate substrate in fully marine waters between 15 and 30 metres, the energy level being higher than in biofacies 3 with gentle to moderate current activity. The presence of a large number of burrowing bivalves indicates that the substrate was soft, while the water was clear and no deposition was taking place.

Biofacies 5 (46 units) Lopha biofacies

This is defined by the abundance of Lopha plicatula, but with important Trigonopora moniliferum, Holoporella desioi and Chlamys spp. L. plicatula typically occurs in fully saline waters between 7 and 30 metres deep and like spherical coralline algae can develop on soft lime mud substrates where the evergy level is rather low. The biofacies, which occurs in limestones (78·6%) and coastal sands (14·8%), has a biotal analysis strikingly similar to that of biofacies 3. Bioturbation affects 36% of the units.

The environment: represents an algal-rich soft lime mud or clastic sand substrate in fully marine waters between 7 and 30 metres deep. The rate of deposition is comparable to that of biofacies 3 in the lime - stones, but is probably very slow in the higher energies of the clastic sands. It probably represents oyster banks within the general environ - ment of biofacies 3.

Biofacies 6 (22 units) Echinolampas biofacies

This biofacies is defined by the presence of Echinolampas sp. together with a stenohaline biota. Its close association with pectinids, Holoporella desioi and Ostrea plicatula suggests that it requires a fairly cohesive substrate in waters of moderate current activity. Its own behaviour indicates that it is rigidly stenohaline, and its restricted distribution in the section makes it clear that Echinolampas could not colonise the area except after prolonged fully marine conditions. The occurrence, bioturbation and biotal analysis are similar to those of biofacies 5 (except that there are rather more scavenging herbivores).

The environment: represents an algal-rich soft carbonate substrate in fully marine waters between 10 and 40 metres, the rate of deposition being very slow or non-existent; slight to gentle current activity is

reflected in variations in the substrate, the optimum being rather coarser than for biofacies 5. The environment probably represents small current-affected sand banks within the general environment of biofacies 3 and 5 developed after lengthy periods of fully marine conditions.

Biofacies 7 (107 units) Crassostrea biofacies

This is characterised by the presence in significant or abundant quantities of Crassostrea gryphoides. The biofacies contains a very large number of groups occurring in rather minor quantities. The feeding habits are in similar proportions to the previous biofacies but there is a marked decrease in the percentage of endobionts, the places of which are taken by burrows.

Coincident with the abundance of C. gryphoides there is an increase in the euryhaline groups, the most typical being Chlamys, astriclypeids, Balanus and Anomia. The salinity range of the biofacies probably varied down to about 10°/oo the maximum growth of Crassostrea being between about 15 and 25°/oo. The abundance of important stenohaline groups makes it probable that the salinity was normal for at least part of the time, and that the lowering of salinity was due to periodic invasions of brackish water. Crassostrea gryphoides indicates depths from 0 to 27 metres so that generally this was a shallow biofacies. It is present in a variety of sediment types, only 52% limestones, the rest being cal - careous sands and shales and sandy limestones.

The environment: represents deposition on a wide variety of algal substrates, calcareous, sandy and clayey, in areas where the salinity fluctuates down to 10°/oo and is normally between 15 and 30°/oo. Though the substrate is variable the energy levels reflect moderate to strong current activity, the clayey beds being cohesive. The depth varies from the intertidal zone down to about 30m. Probably deposition took place near the mouth of an estuary.

Biofacies 8 (26 units) Placenta biofacies

Biofacies 8 is characterised by the presence of Placenta miocenica, a species whose living relatives can tolerate influxes of fresh water. Its depth range includes the intertidal zone down to 20 (rarely 30) metres, where it flourishes in shallow bays and off the mouths of est - uaries. As in biofacies 7 the euryhaline groups are accompanied by many important stenohaline groups so the very variable salinity must again be due to periodic influxes of brackish or fresh water. An in - crease in bioturbation reflects the proximity to shallower waters. 75% of the units are limestones and 8% their associated shales.

The environment: represents deposition on a shallow (0-20 or 30 m) algal lime sand substrate in areas of moderate to high current activity near the mouths of estuaries. The normal marine conditions are subject to influxes of brackish or fresh water and the depositional rate is slow and periodic.

Biofacies 9 (9 units) Idmonea biofacies

This is characterised by Idmonea spp. a fully saline open marine genus, at the present day limited to depths below 20 metres. Its close associates are rather variable but with respect to biofacies 8 there is an increase in stenohaline groups, and in suspension-feeders. There is a decrease in the other feeding types and in burrowing. The biofacies occurs in a variety of sediment types, mainly limestones (33%) and the associated shales (33%) but also in calcareous sands and shales (33%). The proximity of this biofacies to biofacies 6 in the sections suggests they are both related to lengthy periods of normal salinity.

The environment: represents fully saline conditions on a soft lime mud or cohesive clastic mud substrate without algae in water deeper than 20m., (but probably shallower than 50m.). Current activity is gently to moderate.

Biofacies 10 (27 units) Mixed calcareous alga Crassostrea biofacies

This biofacies represents a mixture of many of the biofacies so far described, particularly biofacies 3 and 5, 7 and 8. The biotal analysis represents an intermediate stage between those with predomin - antly stenohaline groups and those with predominantly curyhaline groups. Probably both mixing of salinities during deposition (as in biofacies 7 and 8) and post-depositional mechanical mixing have lead to the present composition. Burrows affect 44% of the predominantly limestone and calcareous sand units.

The environment: represents deposition in variably saline water in areas of gentle to high current activity. The depths range varies from 0 to 30 or 40 metres. 59% of the occurrences in the sections either contain conglomerates or are associated with cross-cutting units, so that many of the units may represent algal channel areas where material from all the environments accumulated.

Biofacies 11 (47 units) Smooth bivalve - turreted gastropod biofacies

This is dominated by smooth bivalves and (a) type turreted gastro - pods, and contains a large and variable biota. The dominance of endo - bionts illustrates the more rapid rate of sedimentation and the softer nature of the substrate. The percentage of stenohaline groups is low but the composition of the more important groups indicates fully marine conditions. Assemblages representing intertidal and subtidal environ - ments of both low and high current activity are represented. The abundant euryhaline groups present indicate proximity to slightly brackish water. A variety of sediments contain this biofacies: limestone (53%), sandy limestone, calcareous sand, and calcareous shale; and 47% are affected by bioturbation.

The environment: represents normal marine and slightly sub-saline conditions on slowly deposited lime. sand, sandy and clay substrates

under conditions of moderate to high current activity. Many of the sediments are intertidal, others are restricted to shallow waters down to about 10 or 15 metres.

Biofacies 12 (13 units) Smooth bivalve biofacies

In relation to biofacies 11, this biofacies is characterised by smooth bivalves only. Gastropods are almost entirely absent, their place being taken by burrowing decapods. In comparison with 11 there is a great increase in the number of suspension-feeders, endobionts and stenohaline forms together with a decrease in the number of herbivorous scavengers and other feeding types. The percentage of burrowing remains the same (48%). The biofacies occurs in limestones (38%) their associated shales (30%) and calcareous sands (23%) mainly.

The environment: represents slowly deposited tidal and very shallow subtidal (down to 5m) calcareous, sand and mud flats subject to moderate to strong current activity. Burrowing and boring groups are the most important, the only epibiontic groups being swimmers. The recent equivalent of this biofacies is the partly protected sands with Callianassa and bivalves of the shallowest Infralittoral of the Mediterranean.

Biofacies 13 (8 units) Turreted gastropod biofacies.

This is characterised by turreted gastropods, a group typical of shallow water sediments near the mouths of estuaries. There is a large percentage of herbivorous scavengers and 62% of the units are burrowed. The biofacies occurs mainly in limestones (50%) and sandy limestones (23%)

The environment: represents a slowly deposited heavily grassy or algal calcareous sand substrate in normal marine waters between 0 and 10 metres deep subject to periodic influxes of brackish or fresh water (bringing in bone material). The energy level varies accordingly

but is generally moderate to high, allowing the presence of a rich burrowing fauna.

Biofacies 14 (13 units) Mixed calcareous algae / bivalve-gastropod Biofacies.

This is a biofacies consisting of spherical calcareous algae associated with smooth bivalves and turreted gastropods, and so forms an intermediate between dominantly epibiotal and dominantly endobiotal biofacies. The epibionts are typical of algal-rich soft lime mud substrates in areas of gentle to moderate current activity. The high percentage of herbivorous scavengers and burrowing (70%) suggests a similarity with biofacies 13. However, the major groups are stenohaline, and the effects of brackish water influxes less. It occurs in limestones (86%) and interlaminated beds(15%).

The environment: represents a slowly deposited algal lime mud and clastic mud substrate deposited in depths of 10 to 30 metres. Current activity is gentle to moderate, but influxes of brackish water are rare. Mixing of biofacies 3 and 11 probably accounts for many of the occurrences.

Biofacies 15 (20 units) Mixed Crassostrea / bivalve-gastropod biofacies

This consists of a Crassostrea gryphoides assemblage rich in smooth bivalves and turreted gastropods and so represents an environment intermediate between biofacies 7 andll. The assemblage is very similar to both except that there is an increase in suspension feeding endobionts and burrowers, and with respect to biofacies 11 there is an increase in stenohaline groups. As in the case of biofacies 14, mixing probably accounts for many occurrences of this biofacies. It is found mainly in limestones (40%) and calcareous sands (35%).

The environment: Represents an algal sandy or silty substrate in areas of moderately high current activity subject to periodic influxes of brackish water down to about 25°/oo. The depth varies down to about 20 metres

Biofacies 11-15 are referred to as the"bivalve- gastropod"biofacies.

Biofacies 16 (16 units) Ribbed bivalve biofacies

This is characterised by ribbed bivalves, but includes important smooth bivalves and turreted gastropods. Ribbed bivalves indicate shallow marine (0- 20m) or brackish water (down to 17°/oo) conditions with variable substrates. The biotal analysis is similar to that of biofacies 11 except that there is a great reduction in stenohaline groups and an increase in bioturbation, (81%). Ribbed bivalve assemblages typified by cockles are found today in bays and lagoons and also on the open shelf where the salinity is suitable. The biofacies occurs in a variety of sediment types, mainly limestones and calcareous sands.

The environment: represents algal-rich sandy areas in salinities varying from 35°/oo to 17°/oo (polyhaline-marine) with slow deposition in moderate to high current activity. The high percentage of bioturbation indicates that the water was very shallow (less than 15m) and that in many cases deposition took place in shallow brackish water bays and lagoons.

Biofacies 17 (15 units) Capsa biofacies

This is characterised by Capsa lacunosa with a similar biota to that of biofacies 16, but with rather more scavenging epibionts and rather fewer suspension feeders. In the finer substrates of which tellines are typical, algal surfaces are common and deposit feeders more important. As with biofacies 16 there is a decrease in epibionts and stenohaline groups with respect to biofacies 11. This biofacies often occurs reworked in clay pellet conglomerates in calcareous sands and limestones in which case it probably represents eroded silt and clay horizons. 67% of the units are bioturbated.

The environment: represents deposition of fine sands and silts (often calcareous) in salinities probably varying down to about 25°/oo. The substrate is rich in algae and like biofacies 16 is deposited in fluctuating currents. It comprises the fine grained equivalent of bio - facies 16, and is either intertidal, shallow subtidal or lagoonal.

Biofacies 18 (16 units) Corbula basteroti biofacies

This is characterised by Corbula basteroti with an associated smooth bivalve and turreted gastropod fauna as before. In comparison to biofacies 16 and 17 there are very few endobionts, but the number of stenohaline groups remains similar. C. basteroti frequently dominates the assemblage to the exclusion of almost everything else in a manner suggestive of a restricted environment. The principle occurrence is in sandy limestones.

The environment: represents deposition in the high energies of low salinity channels in which the substrate was covered with algae. The salinity varied from near normal-marine down to possibly 10°/oo, representing considerable restriction.

Biofacies 19 (10 units) Callianassa biofacies

This is characterised by callianassids by themselves, indicating intertidal or very shallow subtidal conditions. Predictably, 90% of the units are bioturbated. 60% of the sediments in which the biofacies occurs are interlaminated sands and shales and 20% are calcareous sands.

The environment: represents intertidal or very shallow subtidal (down to 5 metres) marine or brackish conditions in areas of moderate to high current activity.

Biofacies 20 (47 units) Continental biofacies

This is composed of continental fossils, the most important of which are dicotyledenous trees, bones and palm trees. The trees and terrestrial vertebrates (mammals) are typical of the banks of rivers in savannah climates, while the sharks, turtles, crocodiles and aquatic mammals are found in rivers and estuaries in the same areas. 57% of the occurrences are in sands, and 22% in their associated shales. Bio - turbation, largely by ichnofacies 8 affects 26% of the units, the few calcareous beds being characterised by Ophiomorpha ichnofacies. One of the characteristics of the savannah climate is the marked seasonal fresh water outflow, which leads to alternate periods of high and low current activity. The periods of high outflow correlate with the fresh and brackish water influxes in the marine biofacies.

The environment: May be divided into three;

(a) Unconsolidated sands with trees and bones represent deposition in river channels subject to periods of high fluvial currents.

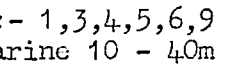
Throughout the rest of the year the rivers were subject to tidal action - indicated by the presence of sharks teeth and Teredo bored wood. The depositional rate was fairly rapid.

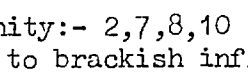
(b) The associated shales with leaves and Hydrobia sp. represent the swales at the tops of the river channels and flood basin deposits.

(c) Thin sandy limestones and interlaminated beds biotur - bated by ichnofacies 1a and 7 represent short lived marine incursions up the river channels.

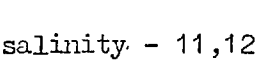
The biofacies may be grouped into three superfacies on the basis of the dominant groups.

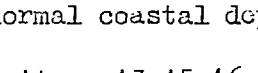
Super Facies (1) Marine, dominant epibionts (indicate slow/non deposition, fairly hard substrate).

(a) Fully saline:- 1,3,4,5,6,9 () i.e. fully marine 10 - 40m

(b) Reduced salinity:- 2,7,8,10 () i.e. subject to brackish influence 0 - 30 m.

Super Facies (2) Marine, dominant endobionts (indicate slow/moderate deposition, soft substrate)

(a) Near normal salinity - 11,12,14,19 (); normal coastal deposition. 0 - 20m.

(b) Reduced salinity:- 13,15,16,17,18 (); subject to brackish influence 0-20m.

Super Facies (3) Continental. 20 ().

CHAPTER 4

THE BIOTURBATION STRUCTURES

Fossil burrows are very common in all of the sediments of the Zelten area, and being always in situ are potentially especially useful in environmental reconstruction. They are in addition frequently pre - served in sands and shales not condusive to the preservation of shelly fossils and so provide a palaeontological continuity through the area that would otherwise be absent.

Their morphology is dictated by the habit and behaviour of the organism that created them however, and may vary, in some cases quite considerably in response to different substratum or environmental con - ditions. Thus one species of organism may be responsible for the cre - ation of a number of different burrow forms. It seems very likely also, that closely related organisms faced with the same environmental con - ditions would behave similarly and produce comparable or identical burrows.

The study of burrows then, is the study of behaviour and habit. Seilacher (1964) has proposed an ethological classification, comprising five groups based upon the function of the burrow. No examples of pascichnia or cubichnia were found in the Zelten area, but not all fall into the remaining three categories of repichnia, fodinichnia and domichnia.

The similarity of structure of the less complex burrows results in the recognition of rather fewer burrows than there probably are. Thus in many cases they have been regarded as the excavations of higher taxa than genera or species and taken to indicate only the broadest aspects of the environment. In addition the lack of detailed descriptions of the burrows of most marine endobionts makes it extremely hard to ascribe

with certainty many fossil burrows to small taxa. In some cases burrows have been described from the Recent that are identical to those in the Zelten area and one can in fact refer them to living genera or species, but even then environmental conclusions cannot be reached with confidence. Nearly all the burrow structures described from the Recent come from intertidal and lagoonal environments, the difficulties of collecting thick undisturbed sediment samples from subtidal deposits having largely prevented their study there.

In short, in spite of their advantages, the attribution of sedi - ments to environments by reference to their burrows, can only be confi - dently undertaken if there is a great deal of supporting evidence.

When assessing the significance of the concentration of burrowing in units, three factors have to be borne in mind:

(i) The suitability of the enviroment and substrate to benthonic burrowers.

(ii) The amount of time the unit remained exposed on the sea floor and was available for animals to burrow into it. i.e. the rate of deposition.

(iii) The amount of subsequent physical reworking of the sediment. Van Straaten (1954) showed that burrowing on the lower tidal flats of the Netherlands was much less than on the upper flats even though the population of living individuals was similar. This was due to marked reworking of the lower part of the intertidal zone.

The concentration of burrowing in a unit is therefore dependent on a number of factors, only one of which is the environment represented by the rock itself. If a burrow present in a bed roots from the base of the unit above, it is important to consider it separately from the environment of the former. The sediment in which it occurs merely acts as a substrate that may change the form of the burrow considerably but often bears no other relation to the conditions under which the burrowing

organism lived. Burrows seem to be much more related to the depositional environment of the unit above, but in many cases like many of the shelly fossils they are not related to any sediment, but correspond to periods represented by non-deposition. In many cases following a period of non-deposition conditions revert to those that prevailed during the deposition of the unit below, and the only evidence of a break in de - position is the presence of a highly burrowed horizon.

Within fluviatile sands at section 30 horizons with marine burrows occur. This does not mean that the organisms that created them could also burrow in a fluviatile environment, they in fact mark short lived transgressions of the sea during which no sediment was deposited.

Seilacher (1964) divided burrow assemblages into three depth facies. All of the burrows from the Zelten area belong to the Cruziana facies, characterised by horizontal and vertical burrows.

In classifying the burrows into types, various principles have been recognised, based on the experience of field examination and subsequent analysis:-

(i) Size is of limited importance in classification.

(ii) Burrows present in different substrates may have completely different forms, but the relationships are shown up by intermediates.

(iii)The branching pattern of burrows tends to be regular in deposit - sifting types, but is on the whole very irregular in deposit-feeding types, being related to particularly nutritious patches of the sediment.

(iv) Many organisms that use the same burrows repeatedly secrete a mucus into the sand around them to hold it together. This is often preserved in sands as a rudimentary wall, and its absence from all bur - rows of one particular pattern may be taken as evidence that the organism did not remain in one burrow for a long time, but was merely a deposit - feeder.

The burrows were distinguished by their morphology and burrowing habit. They fall into the following groups.

(A) Round cylindrical structures

(i) with a lignitic fill: lignitic rootlets in sands (0·1 to 0·4 cm diameter).

(ii) with a shale fill: Argillites in shale (0·9 to 1·5 cm diameter).

(iii) with a silt or sand fill.

(a) branching unwalled structures

Novisa 0·7 cm in diameter in sands and shales.

Needleichnus o·2 to 0·4 cm in diameter, in calcareous sands.

Caegichnus 0·5 to 1·0 cm in diameter, in calcareous sands.

Alukichnus 1·0 to 2·0 cm in diameter, in calcareous sands.

Thalassinoides 0·5 to 11 cm in diameter, form regular plexus in shales.

(b) branching walled structures

Dikaka 1·5 to 2·0 cm in diameter, in sands irregular gypsum cemented wall.

Ophiomorpha 0·5 to 11 cm in diameter, in calcareous sands, regular warty silty wall.

Aestites 1·5 to 7 cms in diameter in sandy limestones regular thick smooth calcareous wall.

Capsites 0·5 to 2·0 cms in diameter, in calcareous sands, thin smooth silty wall.

(c) unbranched, U-shaped structures

Diplocrateron 2·0 cms in diameter, often with spreiten, in interlaminated beds.

Corophioides 0·2 to 0·4 cm diameter, without spreiten, in calcareous sands.

(B) Flattened cylindrical structures

Premerites 0·2 to 0·6 cm diameter in cal - careous sands.

(C) Flattened fan-shaped structures

Spreitichnus 1·5 cm thick, in calcareous sands.

(D) Globular structures

Globichnus 5 cm in diameter, in calcareous sands.

(E) Radiating structures

Faecal mounds 14·0 cm across, in sandy limestones.

(F) Traces

Scutellichnus 4·0 to 7·0 cms across meandering, in limestones.

In addition a few rounded accumulations of sand 0·5 to 0·8 cms in diameter have been described.

The order of description groups those burrows that are thought to be related. Those structures thought to have been created by plants are treated first, and those thought to have been created by higher animals last.

Occurrence of the bioturbation structures

STRUCTURE	n° of units	% occurrence in seds.								abundant			% association with biofacies/burrows					
		limestn.		calcareous			sandy	uncon.		common								
		lst	shale	snd	sh	int	lstone	snd	sh	rare			over 90	80-90	70-80	60-70	50-60	40-50
Dikaka	7							100		100								
Lignitic rootlets	7							100		62	38						Novisia	
Novisia	8							50	50	60	40							
Argillites	8				30	60				16	84							
Needleichnus	87	15		31		32	9			15	68	13						
Premerites	17	12		47		29	12			30	70							
Caegichnus	145	23	2	15	3	30	27			17	72	11						
Alukichnus	39	23	2	31	3	18	23			29	63	8						
Capsites	48	40	2	11		7	21			22	68	10						
Spreitichnus	6					50	50			28	72							
Corophioides	5			20		20	60				20	80						
Diplocraterion	11			18		72	9			22	33	44						
Ophiomorpha-Thalassinoides	308	26		28	4	38	3			10	68	72						
Aestites	40	2		10		5	83			7	53	40						
Globichnus	12	9		33		25	33			50	50							
Scutellichnus	1	100									100							
Faecal mounds	4	25		25			50			100								

Dikaka (Glennie & Evamy 1968)

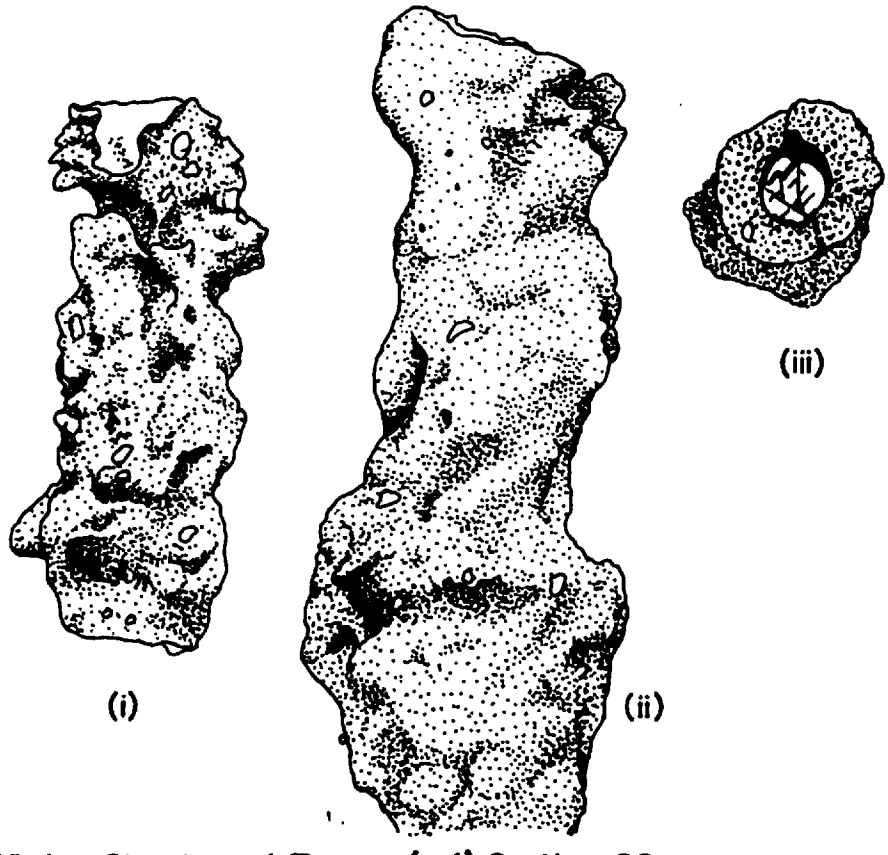
Description: These consist of 1·4 to 2·2 cm diameter vertical, steeply inclined and horizontal tubes with an extremely irregular bul - bous gypsum cemented 0·2 to 0·5 cm thick casing (figure 4. 1a(i),(ii)). The central portion is filled with partly cemented impure sand, silty sand or silt (figure 4. 1a (iii)), while the case is composed of host rock - poorly sorted pure crossbedded sand, the foreset pattern of which passes through the casing undisturbed.

The outer surface is irregularly warty, 1·0 cm diameter protuber - ances arising from it. Those examples smaller than 1·8 cm diameter are considerably smoother, less warty and less variable in diameter than the larger ones.

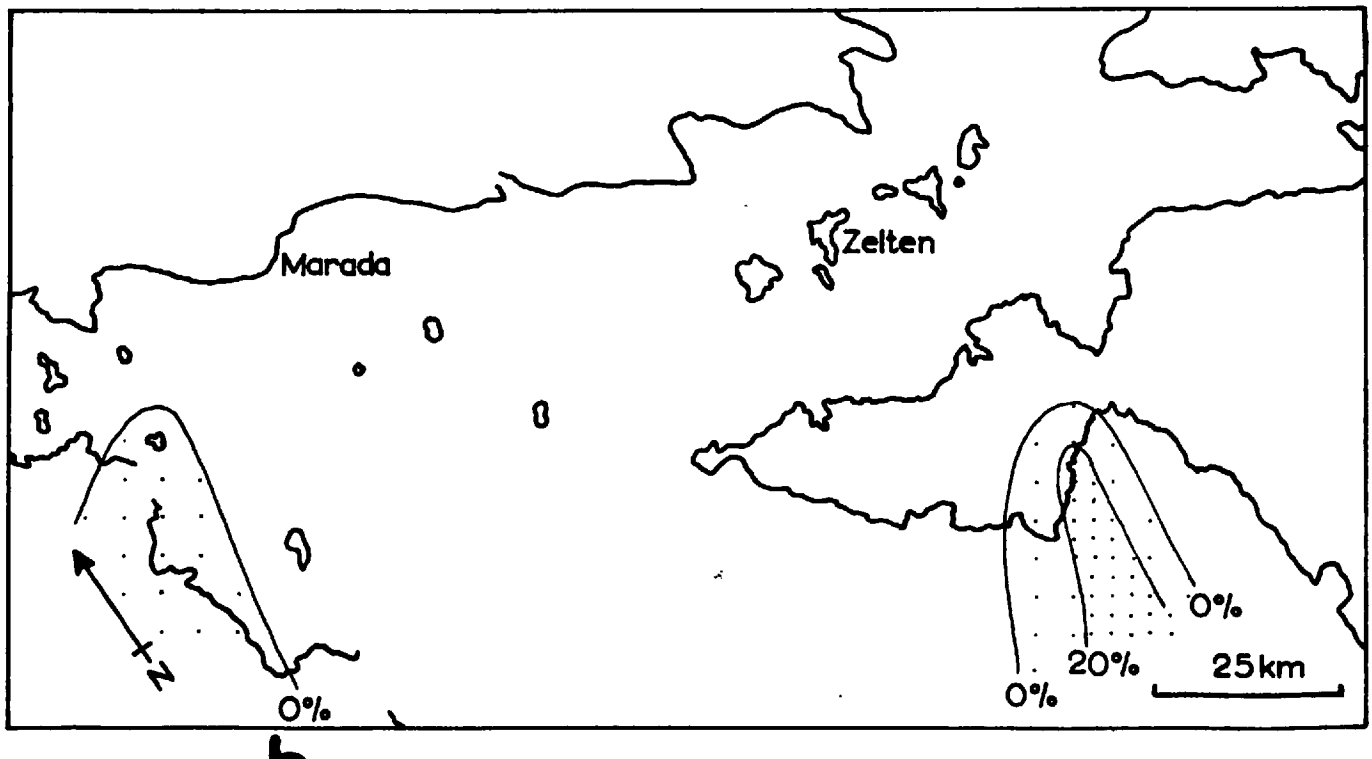
Occurring in unconsolidated sands, these casts stand out when the wind winnows the surrounding sediment away. In exposure vertical or steeply inclined tubes are at least two metres long, while horizontal members may be straight for over four metres. Typical concentrations of 33 vertical tubes per metre^2, and 22 horizontal tubes per metre^2 persist in beds for up to 125 metres laterally. These structures nearly always root from horizons within a metre of overlying lignitic silty shales.

Geographic distribution: Dikaka occur in 7 sand units, all in - terpreted as fluviatile point bars or levees, in 5 of which biofacies 20 is found. They are restricted to the bases of the sections on the south side of the Jebel Zelten, but also occur at section 19, (Garet el Luban).

These structures are presumably (in part) those noticed by Savage (1965) in the sands of the Jebel Zelten and described as "sandstone casts of trunks, branches, and roots of trees and probably shrubs". (Figure 4. 1b).



a Dikaka Glennie and Evamy. (x1) Section 30.
(i) and (ii) Specimens showing irregular outer surface.
(iii) Section of specimen showing silt fill.



b Percentage distribution in sections of Dikaka.

Figure 4.1

Interpretation: These structures are very similar to the irregular casings of roots and rootlets of grasses, shrubs and trees widespread in levee deposits at the present day (see Allen 1965). Typically red and brown coloured zones of oxidation surround decaying roots, but sec - retions from plant roots leading to gypsum and calcite-cemented sandstone tubes 0·5 cm diameter have been reported by Glennie and Evamy (1968), from dune sands in Abu Dhabi and Libya. Such structures - in this case called Dikaka, criss cross the bedding.

The widespread distribution of rootlet casts about a metre below the overlying shale units indicates an environment near the top of fluvial channels, perhaps on the levee or the top of the point-bar.

Lignitic Rootlets (Figure 4. 2a)

Description: These are not strictly trace fossils but are closely associated with Dikaka and deserve mention. They consist of 0·1 to 0·4 cm diameter smooth lignite-filled tubes, typically vertical for over 2 metres, but in some cases inclined or even horizontal.

They occur towards the top of unconsolidated sands, interpreted as fluviatile point-bar or levee deposits, rooting from the silty or shale unit above or from very lignitic interfaces. Most commonly only one occurs in every metre of vertical section but in some cases the bed may be crowded with them.

Geographic distribution: Present in 7 units, all unconsolidated sands near the bottoms of sections on the south side of the Jebel Zelten and section 4.

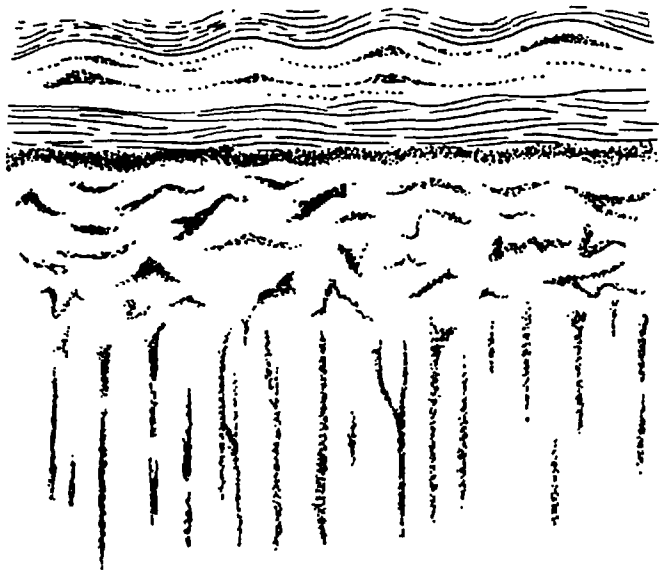
Interpretation: Lignite filled tubes of this type are very common throughout Recent continental sediments where the ground is covered with grass or marsh plants, their presence rooting from near silts or shales suggests an environment near the top of levees or fluvial channels.

Novisia nom. nov.

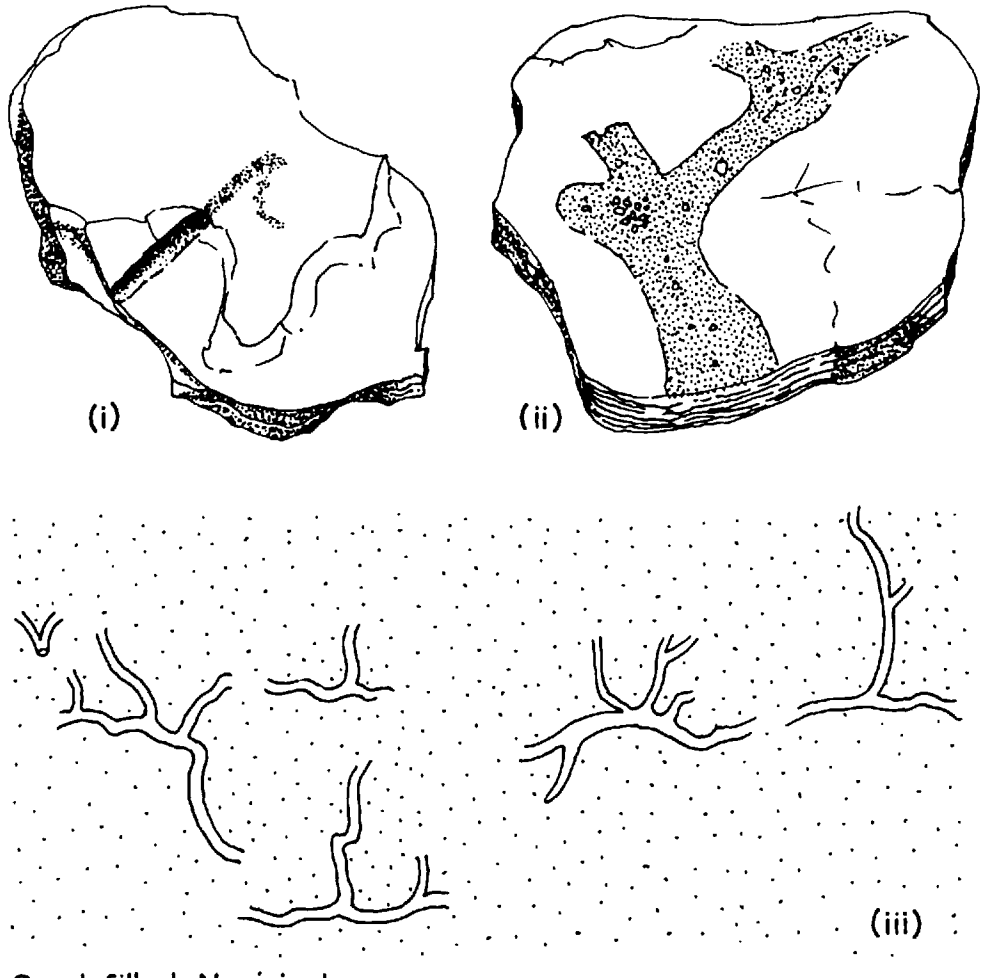
Description: These consist of sand-filled rather sinuous meandering burrows 0·7 cm diameter (0·2 to 2·1 cm), without cases, occurring in sands and silty shales. Those in sands are vertical and horizontal - branching forms, with internodes about 4 cms long. The fill is uncon - solidated sand, ferruginous sand or limy sand and there may be a diffuse lignitic lining (figure 4. 2b (iii)).

The representatives in silts and shales are normally horizontal, ferruginous-sand filled, and strongly depressed (figure 4. 2b (i) (ii)). The diameter varies from 0·2 to 1·6 cm, and the thickness is never more than 0·25 cms. The host rock is compacted around the burrow indicating that the depression is not a primary feature, but is due to compaction. The pattern of burrowing is similar to those in sands; meandering or straight horizontal internodes about 2 cm long are linked by infrequent round vertical tubes up to 2·1 cm diameter. In a unit near the base of section 30, a burrow 0·13 cm diameter filled with large quartz grains in a limonitic silty-sand matrix has a wall composed of irregularly disposed warts 0 02 - 0 06 cm diameter. These probably represent faecal material (figure 4. 3a).

Geographic distribution: Novisia burrows occur in 8 units, four times in fluvial sands and four times in their associated overlying silts and shales. They are associated with lignitic rootlets in three of the sand units, and with the continental biofacies once. In the sands the concentration is only important at horizons rich in limonitic concretions, or lignite. Normally there is only one branching system per metre^2 of vertical face. In the silts and shales the burrows only root from in - terlaminae with scatterings of quartz grains, and are related to periods of non-deposition when thin washed of sand covered the tops of the



a Vertical face of sand showing lignitic rootlets arising from a lignitic horizon. Section 30



b Sand filled Novisia burrows.

(i) 0·25cm diameter horizontal branch in shale. (x1) Section 30

(ii) 1·0 to 1·5 diam. flattened horizontal branch in shale. (x1)

(iii) 0·5cm branches in vertical face of sand. (x0·3) Section 31

Figure 4.2

fluvial channels, and filled the burrows. They are restricted to the bases of sections on the south side of the Jebel Zelten and at section I8.

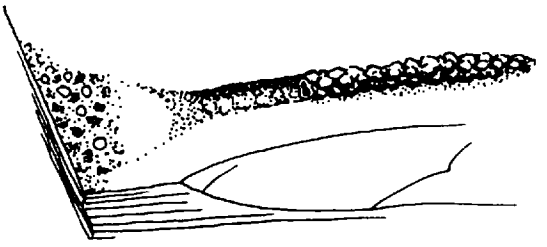
Interpretation: These burrows closely resemble members of the Caegichnus group, but differ in that they burrow in both shales and sands, and are associated with a continental biota. They probably represent fresh or brackish water Fodinichnia burrowing into the point bars of fluviatile channels.

Argillites nom, nov. (fig. 4. 3b)

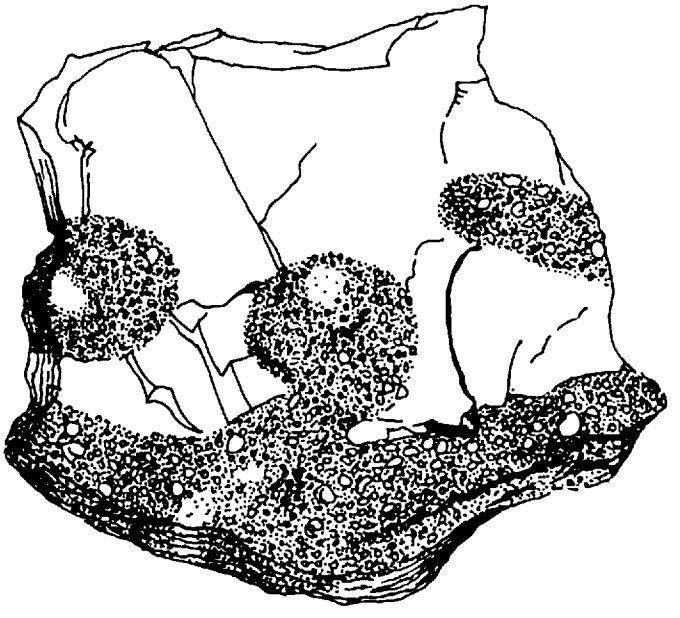
Description: Vertical, inclined and horizontal uncased cylindrical burrows filled with a mixture of sand and clay occur in a few interlaminated shales and sands. The vertical or steeply inclined portions are 0·9 - 1·5 cm diameter, cylindrical, unbranched, and filled with rounded medium sand grains, carbonate powder or fossils, in a shaly matrix. The concentration of sand grains is fairly constant through the radius, but there is always a central portion 0·2 to 0·5 cm diameter which is exclusively shale-filled. A horizontal lamination brought out by bands alternately richer amd less rich in quartz grains or carbonate, is probably due to compaction (figure 4. 3b). The horizontal or low angled portions tend to occur on thin sandy interlaminae and are very similar to the horizontal portions of Novisia in shales. As with the latter they are strongly depressed, the width varying from 0·7 to 1·1 cm and the thickness from 0·2 to 0·3 cm. There is much less obvious silty shale material than in the vertical components, nearly all the material being ferruginous sand. Y - branches about every 2·5 cm lead to a horizontal close knit plexus of burrows. Components may double back upon themselves on adjacent sandy interlaminae.

Geographic distribution: Argillites burrows occur in 8 units, 6 of which are silts and shales with impersistent sandy interlaminae, and the other 2 are shales. The only other burrow they are associated with is Thalassinoides (twice), but marine fossils belonging to the Callianassa, spherical calcareous algae and Trigonopora biofacies occur in 5 units. They are present in sections from west of Raguba to Zelten, dying out northwards and southwards (figure 4. 3c).

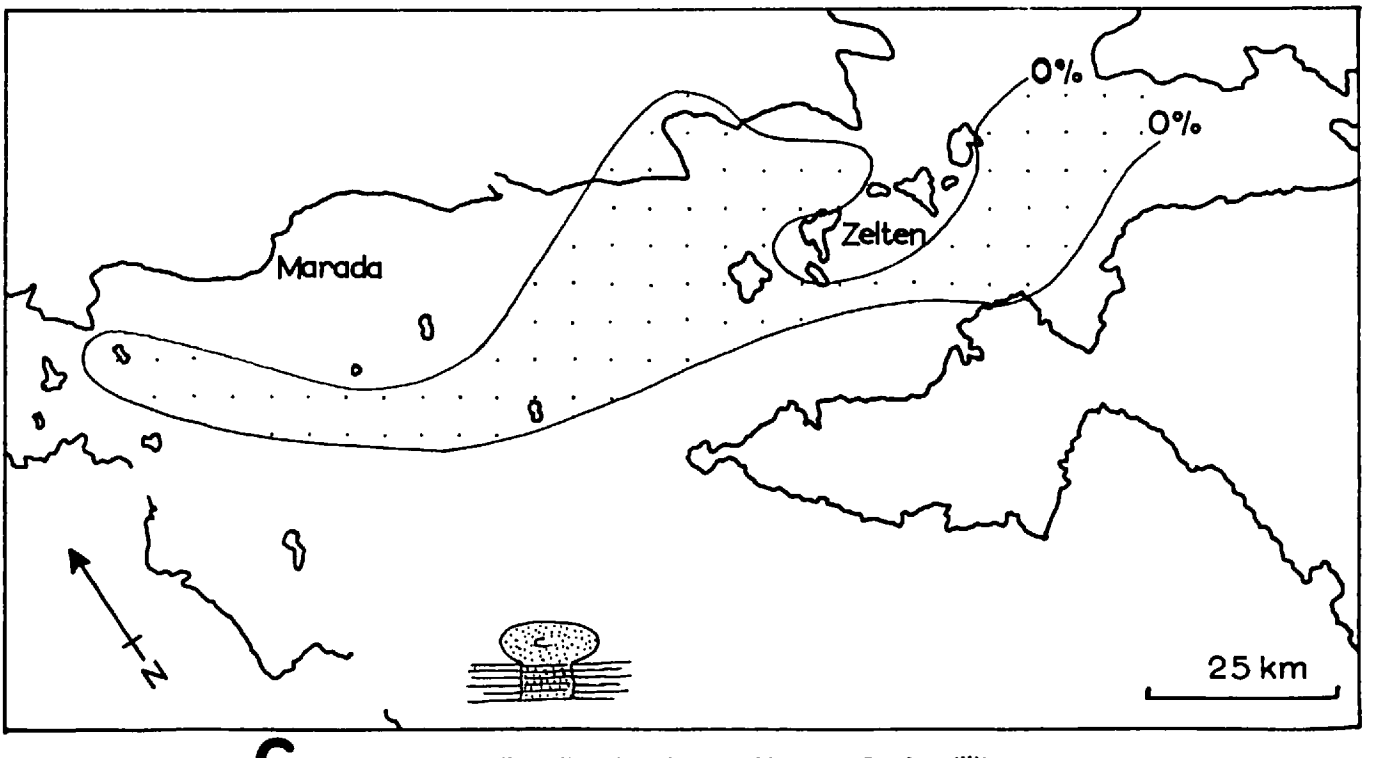
Interpretation: The burrows are very similar to Novisia, but differ in having abundant silty shale material in the vertical portions



a Faecal pellet-filled limonitic Novisia in shale. (x3) Section 30



b Argillites burrows in shale. Both horizontal and vertical portions are represented. Note illsorting of sand grains. (x1·5) Section 18.



c Percentage distribution in sections of Argillites.

Figure 4.3

of the burrow where it passes through shaly sediment. In the horizontal portions where it passes along thin sandy interlaminae, the fill is largely sand. This lack of mixing of the sediment indicates that the organism responsible did not retain the sediment but excreted its faeces as it burrowed. It is the only burrow from the Zelten area excavating shales that does not have an exclusively sand fill indicative of constant re-excavation. The organism was clearly therefore purely a deposit feeder, and one that did not retain a permanent tunnel. Its distri - bution and associates suggests that it burrowed in coastal mudflats. It falls into the category of Fodinichnia of Seilacher (1964)

Needleichnus nom. nov. (figure 4.4)

Derivation of name: refers to the needle like appearance of these burrows.

Description: Needleichnus burrows are small branching sand filled tubes 0·2 to 0·4 cm with rare branches up to 0·6 cm in diameter and are common in many sand units. (Maximum concentration 160/m^2).

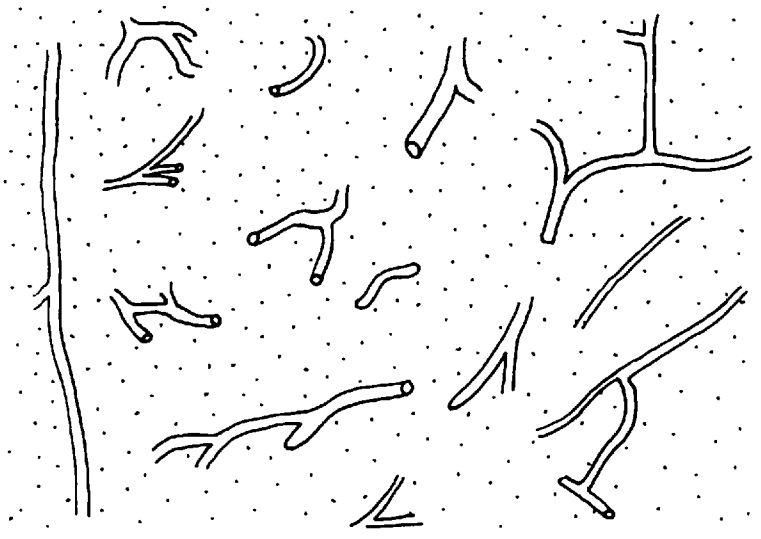
The pattern of burrowing is very variable, some specimens having internodes 7 cms long, while others anastomose closely. Both vertical and horizontal components are represented: The former are usually straight and up to 10 cm long but may incline 60° away from the vertical or may meander and branch dichotomously. Frequently foreset laminae are burrowed (figure 4. 4c). Horizontal components are meandering or rarely straight components branching insensibly every 3 to 4 cms or so both dichotomously and polychotomouslyat 90° or Y-fashion (figure 4. 4 a).

The fill is variable, but usually consists of well sorted sand with or without a calcareous cement. It may however, be silt or a mixture of sand and silt and have a thin silty wall resulting in a concentric lamination.

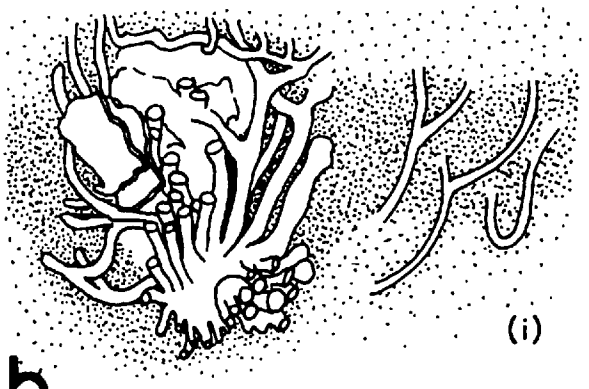
A few examples arise from small globose bodies about 2 cms dia - meter and radiate outwards and upwards for 2 to 3 cms. As these struc - tures have as many as 50 tubes arising from them, they appear stellate. The core is a domed sand filled chamber with a flattened base (fig. 4. 4b).

Geographic distribution: These burrows occur largely in inter - laminated sands and shale and calcareous sands and are closely associated with other burrows, especially Ophiomorpha and Caegichnus. Marine bio - facies occur very frequently, the commonest being the Crassostrea, ribbed bivalve, smooth bivalve-turreted gastropod and Callianassa bio - facies, indicative of a wide range of salinities in very shallow waters.

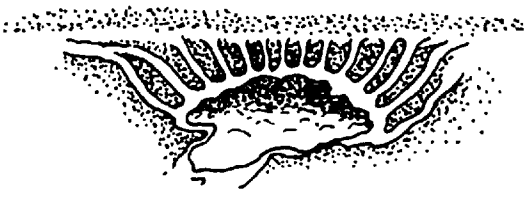
a



Horizontal surface of calcareous sandstone with Needleichnus. (x 1) Section 36



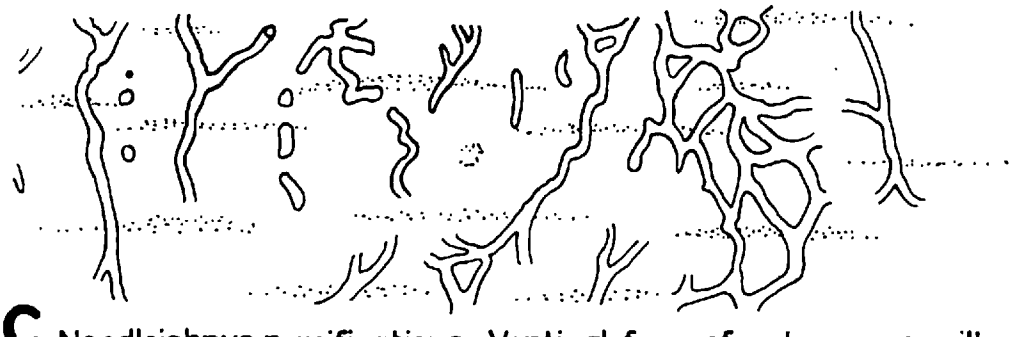
(i)



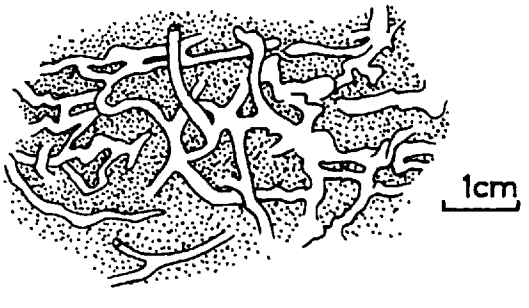
(ii)

b (i) Stellate body with Needleichnus arising from it. Vertical face of sand. (x 1) Section 36.

(ii) Flat based chamber with Needlichnus radiating upwards from it. (x 1) Section 35



c Needleichnus ramifications. Vertical face of calcareous silt. (x 1) Section 16



d Burrows of Scoloplos armiger from a vertical section of a sand flat. (North Sea, after Reineck 1967)

Figure 4.4

Interpretation: The variety of habit indicates that this burrow probably represents Fodinichnia of more than one organism - a deposit feeder within sandy sediment. Closely anastomosing plexi of vertical and subhorizontal burrows resemble complexes produced at the present day by Scoloplos armiger in the tidal sand flat of the North Sea (fig. 4. 4d) (Reineck 1967). Some horizontal radiating unbranched straight or meandering forms may represent faecal casts, like those of Arenicola marina (photo 4. 5b).

From the evidence the environment in which these burrows were formed seems to closely tie in with the sandy tidal flats typified by Ophiomorpha and the euryhaline epi and endobiontic fossils.

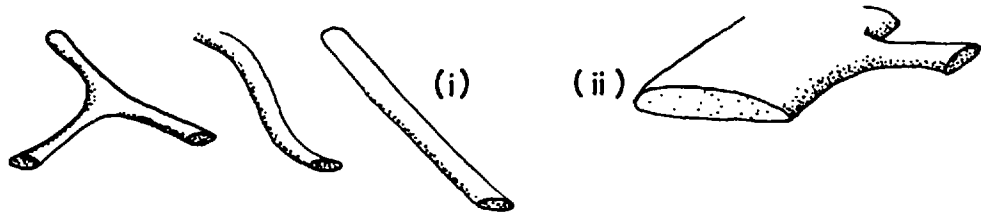
Premerites nom. nov. (fig. 4. 5)

Derivation of name: refers to the flattened nature of the burrow.

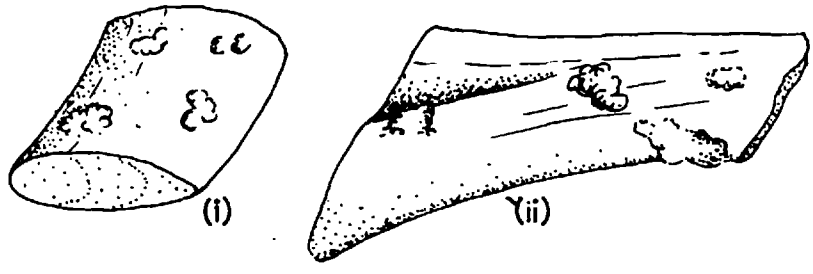
Description: Tubular burrows, strongly depressed in cross section and generally inclined between 10° and 45° from the vertical, occur in several sandy units. A typical specimen measures 0·6 cm x 0·2 cm in section, though the longer axis varies from 0·4 cm to 3·5 cm (fig. 4. 5a). Often there is a considerable variation along one burrow; a specimen 42 cms long varies from 1·2 to 3·5 cm in diameter. The burrow is usually straight with a slightly calcareous silty case 0·1 cm thick, the surface of which is smooth but is ornamented with one or two longitudinal striations and diffuse warty lumps 0·2 cm diameter (fig. 4. 5b (ii)). The fill is usually sand and in some specimens a sideways meniscus fill is brought out by sandy or silty bands 0·03 cm thick every 0·2 cm or so (figure 4. 5b(i)). In some specimens 90° or Y-branching occurs.

Geographic distribution: Premerites is typical of calcareous sands and is always associated with other burrows, especially Caegichnus, Ophiomorpha and Needleichnus. It is not very closely associated with fossils and the biofacies represented are not very indicative of a particular environment. It dies out east and west.

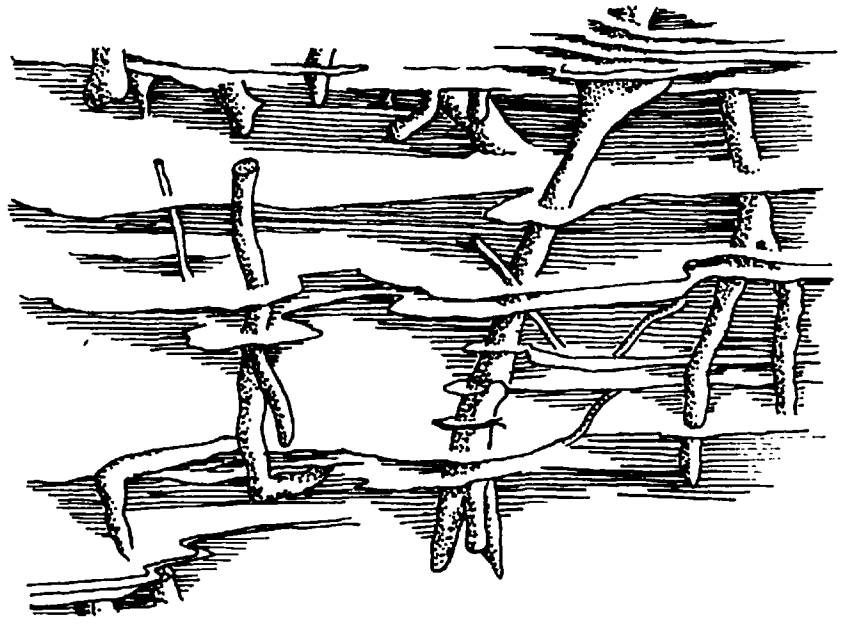
Interpretation: Premerites represents the Fodinichnia of a deposit feeding endobiont that reworked the sediment sideways along the length of the burrow. The strong depression cannot be attributed to compaction in view of the sideways meniscus structure, and its presence in sandy sediment in which the rest of the burrows are unaffected.



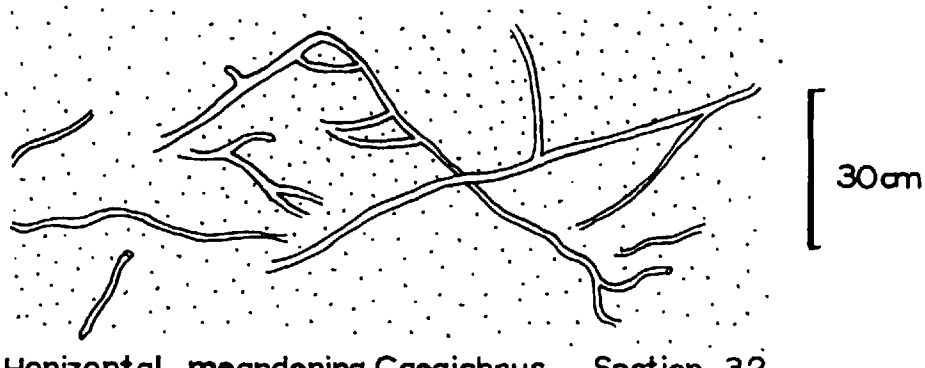
a (i) Inclined branching Premerites. (x1) Sandy limestone, section 16
(ii) Large branching Premerites. (x1) Section 19



b Premerites (x1) Section 19
(i) Section showing sideways meniscus fill.
(ii) Branching specimen with surface warts and striations.



c Irregular vertical Caegichnus. (x1) Section 31
Calcareous sand with thin sandy interlaminae.



d Horizontal meandering Caegichnus. Section 32

Figure 4.5

The Caegichnus group (figures 4,5,6)

Description: The Caegichnus group comprise a large number of types probably produced by a multiplicity of species. They are not sufficiently differentiated from each other to enable much division. Three main types have been recognised, however.

4) Caegichnus: Uncased burrows generally less than 1·0 cm in diameter.

These burrows, which vary from 0·4 to 1·2 cms diameter are extremely common in calcareous sand units though the concentration is very variable. They do not have a casing, though around parts of some there may be a slightly more calcareous silty or lignitic portion that stands out.

Vertical, horizontal, inclined, and meandering elements are present in abundance, all branching frequently (figure 4. 5 c,d). One or two regular patterns may be recognised however - in sandy limestones straight burrows inclined at about 40° criss cross the bedding to produce a characteristic reticulate pattern (photo 4. 1a), while irregular sinuous vertical burrows about 1.2 cms long with complex horizontal plexi at various levels affect calcareous sands (figure 4. 5c). Exclusively horizontal burrows meander along the top surface of some sandy limestones, with variable internodes some over a metre long (figure 4. 5d). The burrows hardly ever affect shales, but may burrow vertically through thin beds to excavate sands beneath (figure 4. 6a (i)).

Branching is usually very frequent (internodes on average 2·5 cm long) and may be Y-fashion or 90° in every plane, dichotomous or poly - chotomous. Short, blindly ending branches 0.3 cm diameter are common.

The fill is commonly ironstained, gypsiferous or calcareous sand but some are rich in calcilutite laminae showing up a meniscus or con - centric structure (figure 4. 6a(ii)).

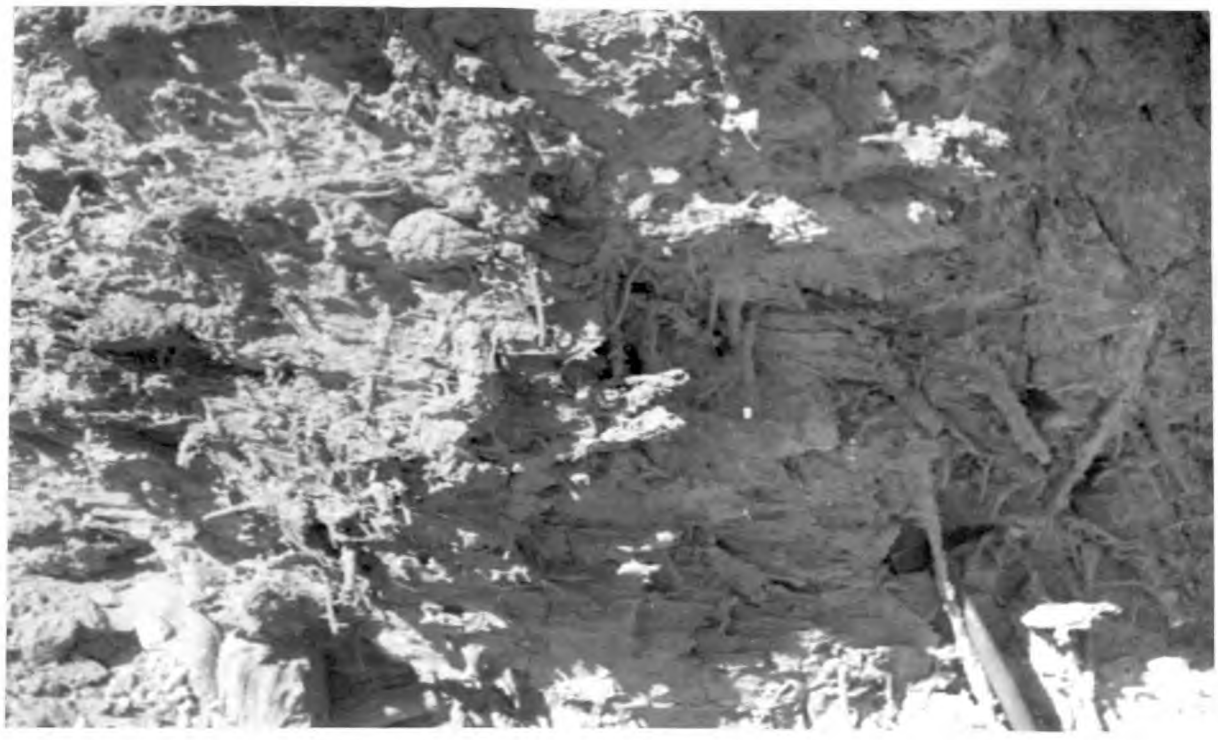


Photo 4.1a. Vertical section of calcareous sandstone with Ophiomorpha Globichnus, Spreitichnus, Alukichnus and criss-crossing Caegichnus (especially on the right)

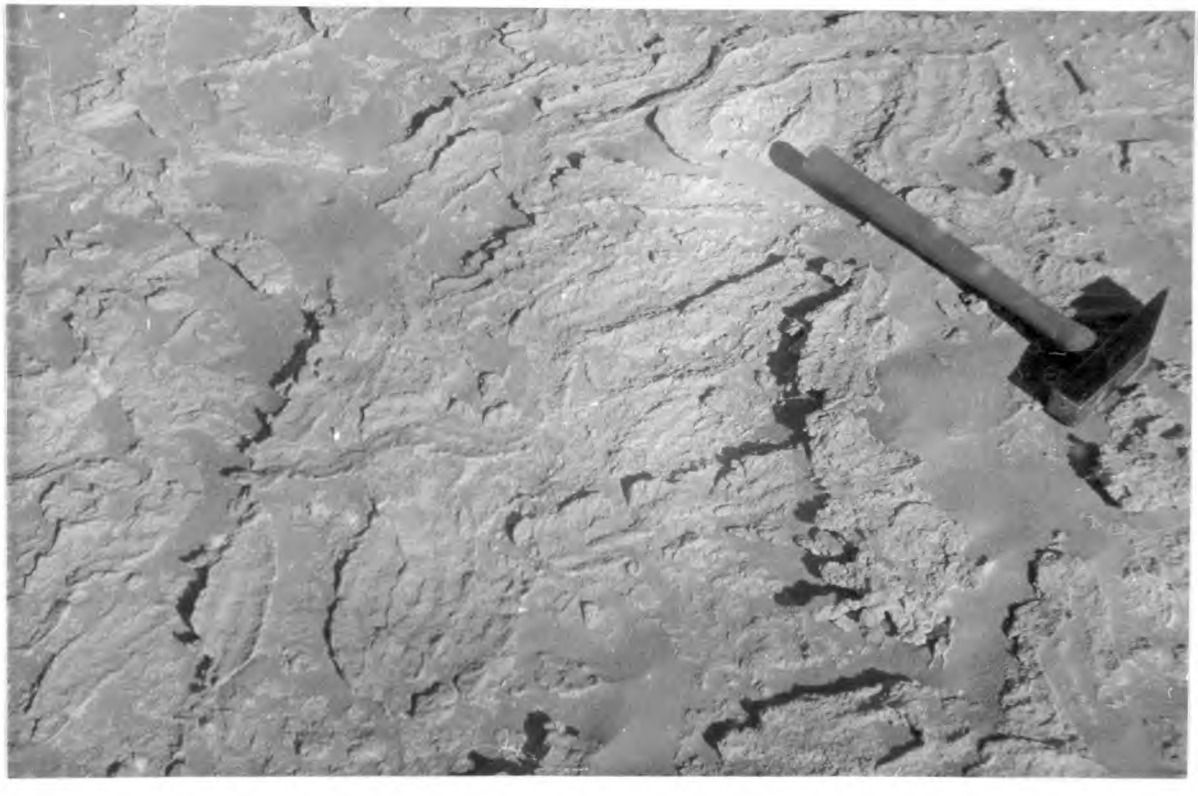


Photo. 4.1b. Scutellichnus trails on surface of calcarenite Section 23.

B) Alukichnus nom. nov. Those generally between 1·0 and 2·0 cm diameter (fig. 4. 6B).

These comprise sand-filled branched and unbranched burrows generally between 0·7 and 2·0 cms in diameter but with blindly ending branches as little as 0 4 cms in diameter. As before vertical, horizontal and meandering elements are present, 15 cm long markedly sinuous vertical components giving off horizontal branching plexi. Branching is very irregular, of Y or 90° type (figure 4. 6b(i)).

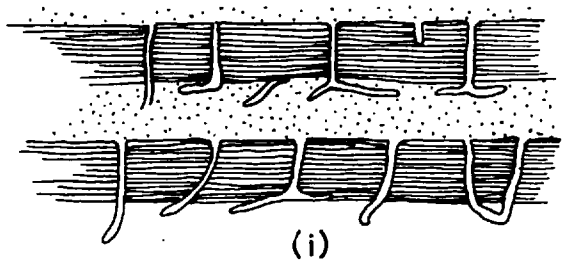
The concentration is usually less dense than that of Caegichnus but may reach 200 components per m^2.

At the base of the autochthonous oyster reef at section 17 these burrows occur around the bases of Crassostrea gryphoides following the outline of the shell. They clearly burrowed during the early stages of reef growth (figure 4. 6b (ii)). At section 5 a limestone unit is riddled with horizontal and inclined 2·0 cm burrows up to 15 cms long forming sensible concentric unbranched furrows about 2 cms apart.

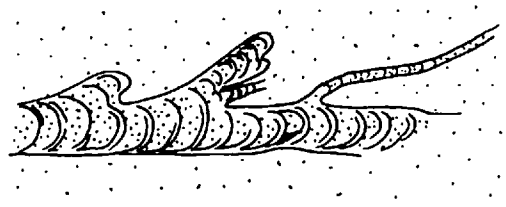
C) Capsites nom. nov. Representatives of both (A) Caegichnus and (B) Alukichnus that have cases (figure 4. 6c).

These consist of burrows very similar to both Caegichnus and Alukichnus but with a continuous 0·1 or 0·3 cm case of more calcareous or silty material. Smaller branches 0·4 cm diameter have cases 0·05 cm, and rare examples have irregular cases 0·6 cm diameter. A meniscus structure is often present in the sand fill.

Geographic distribution: Caegichnus occurs in a wide variety of rock types fairly closely associated with other marine burrows and with marine fossils dominated by the Crassostrea, smooth bivalve-turreted gastropod and Lopha biofacies. It thus indicates a wide range of marine environments, variable in salinity, depth and substrate.



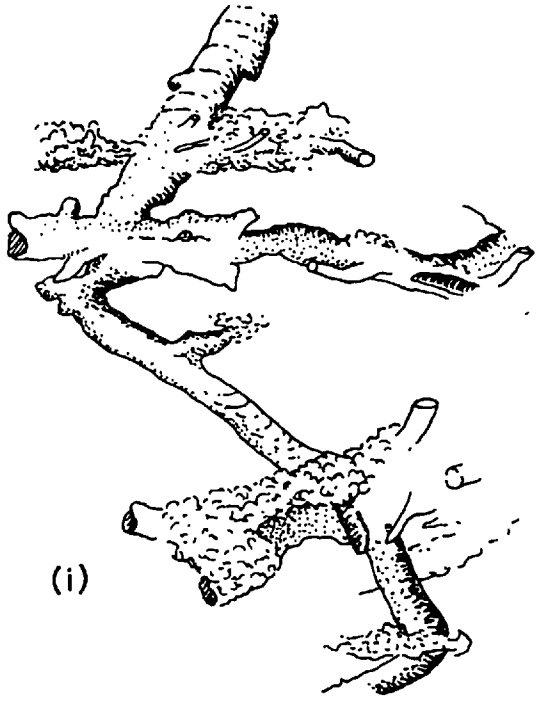
(i)



(ii)

a (i) Caegichnus passing directly through shales and excavating sands. (x0·05) Section 32

(ii) Caegichnus with meniscus fill indicating movement towards the the left (x 1) Section 17



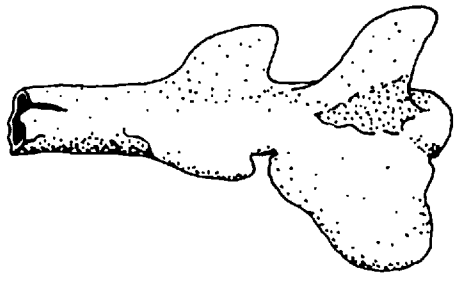
(i)

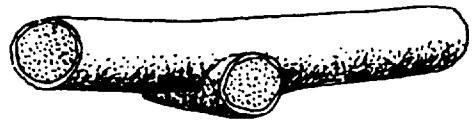


(ii)

b (i) Alukichnus. Vertical meandering type in calcareous sand. (x0·5) Section 30.

(ii) Oblique underview of Alukichnus at base of Crassostrea reef. (x0·3) Section 17.





c Branching Capsites specimens (x1) Section 30

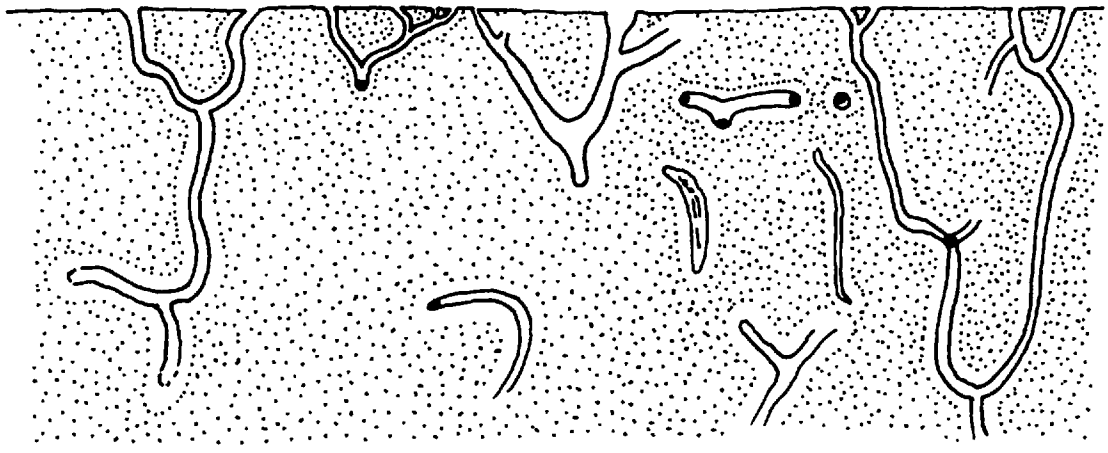
Figure 4.6

Interpretation: Irregular branching sand-filled burrows similar to these forms are commonly produced by scavenging polychaetes in muddy sands in the tidal flats of the North Sea coast. Examples of concentrically-walled burrows with vertical components passing sinuously downwards to depths of 30 cms or so are common. They branch occasionally and give off close knit meandering subhorizontal plexi along the junctions of sandy and clayey horizons and at organic - rich levels. The most common burrower is Nereis diversicolor (figure 4. 7) the tunnels of which are generally less than 1•0 cm diameter. Similar burrowing structures are not common below the intertidal zone though Schafer (1962) found Nereis in channels down to 20 metres, and agglutinated tubes of polychaetes occur down to 60 metres.

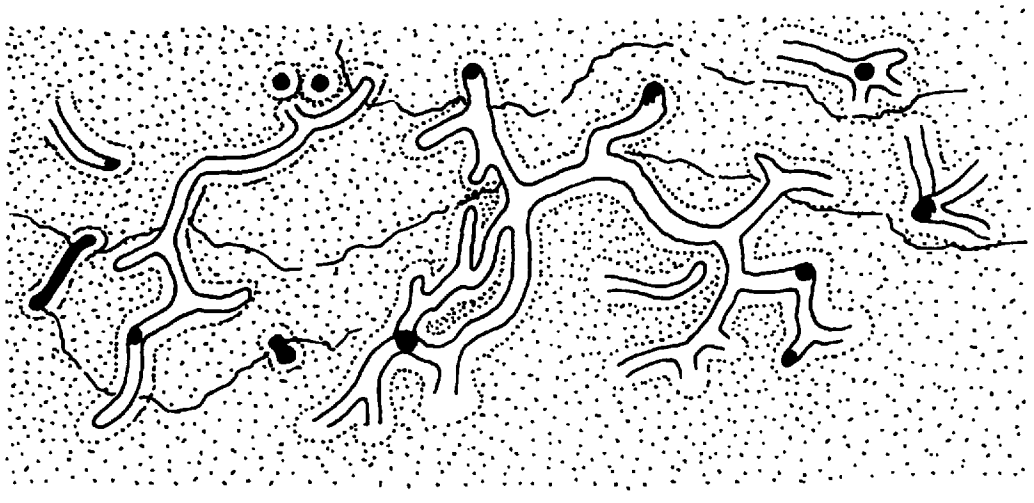
The variations in size and burrow pattern of the Zelten specimens make it certain that these forms were produced by several organisms, so strict environmental reconstruction based on the habits of Nereis cannot be made. Probably most of the burrows are the work of polychaetes, a group which is widespread intertidally and subtidally, though a few may be caused by crustacea.

Their association with a wide variety of other burrows and fossils in a variety of substrates suggests that they are not exclusively intertidal, but they probably characterise intertidal and shallow subtidal deposits.

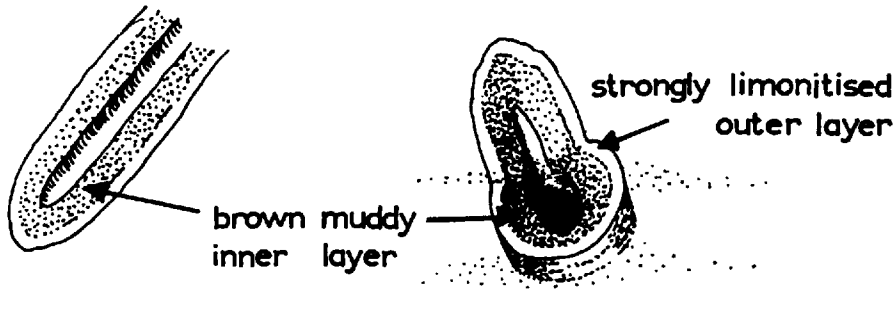
Burrows of the Caegichnus group are similar to simple but generally poorly known sand-filled Fodinichnia from various levels in the geological column, e.g. Balanoglossites, Lennea, Planolites.



a Vertical section through a muddy sand flat with burrows of Nereis diversicolor. Blakeney, Norfolk. (x1)



b Horizontal section 3cm below the surface of a muddy sand flat. Plexus of N.diversicolor burrows in organic-rich horizon. (x1) Blakeney, Norfolk.



c Details of the wall structure of N.diversicolor burrows, illustrating the relatively hard limonitic case that develops. (x3) Eroded out of a sand flat by an intertidal creek. Blakeney.

Figure 4.7

Spreitichnus nom. nov. (figures 4. 8, 9).

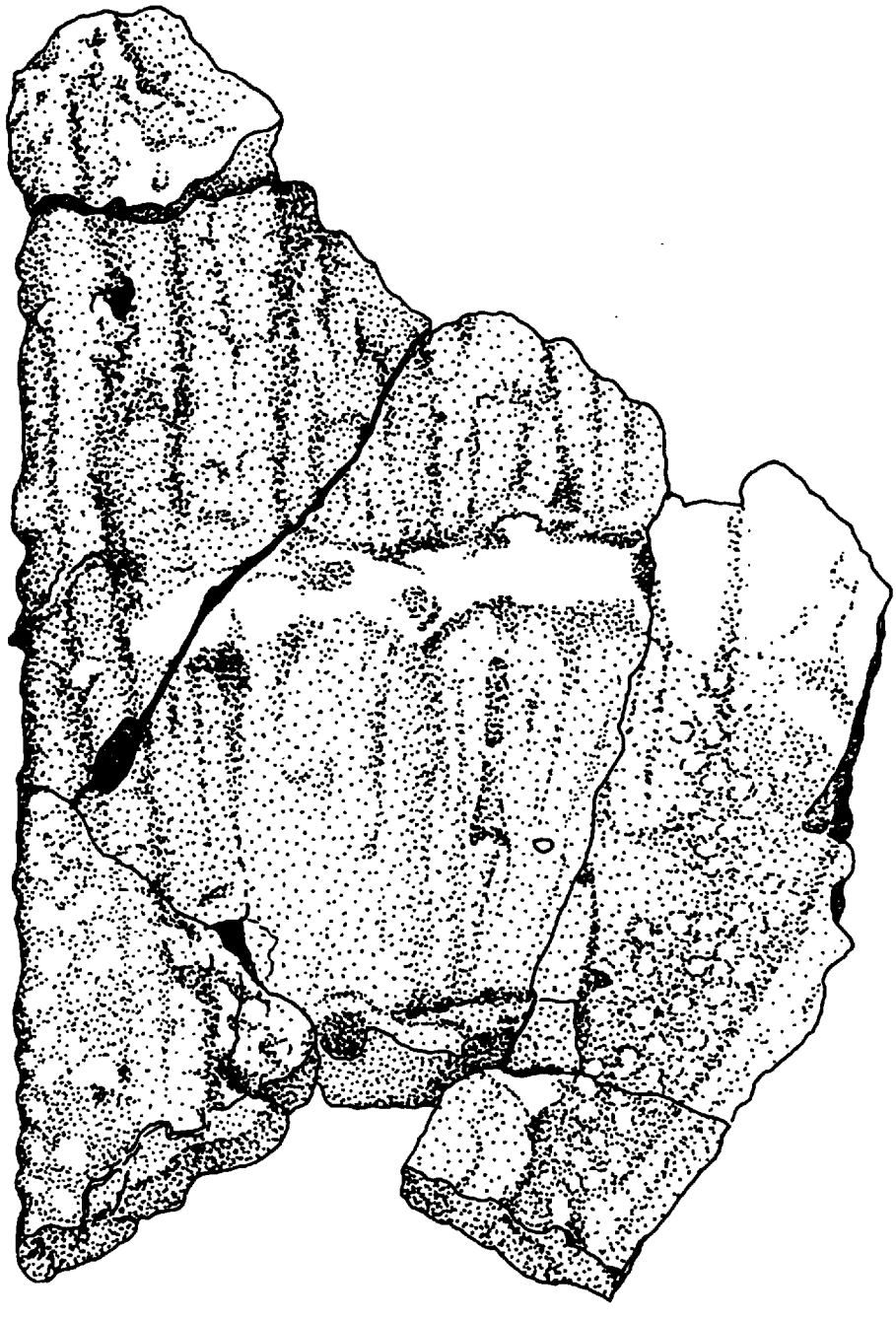
Derivation of name: Refers to the thin fan-shaped "spread" characteristic of the burrow.

Description: These comprise generally vertical fan-shaped burrows with a radial surface groove pattern. In the specimen from section 30 (figure 4. 8), one end of the fan is vertically disposed in the sediment, the other is at about 60° from the vertical. It varies from 1·2 to 1·45 cms thick and is over 30 cms tall. The surface grooves, 0·8 to 1·3 cms apart follow the fan shape and are separated by discrete bulbous portions. They are manifest within the burrow by a vertical meniscus fill brought out by 0·05 cm thick calcareous bands (figure 4. 8b). The meniscus is concave towards the vertical , leaving a final tube 1·4 cms diameter. Scattered low warts 0·6 cms diameter cover 40 - 50% of the surface. The sand fill is generally better sorted than in the sediment. In the same unit there is a specimen forming a fan in a 45° plane and another in a horizontal plane.

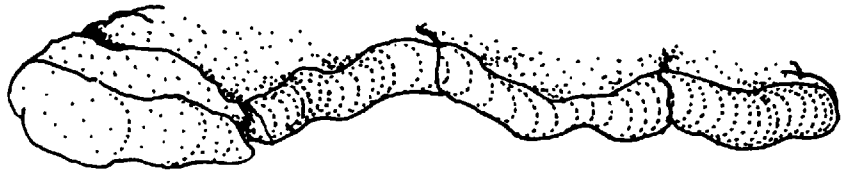
Many smaller specimens are irregularly corrugated in the plane of the fan so that the burrow becomes much thicker (figure 4. 9a) The longitudinal meniscus fill may be seen following the corrugation. Fre - quently the traces of cross bedding are preserved on the surface. In some units there are 2 in a square metre of vertical section.

Dimensions of Specimens:- in centimetres

	Disposition	Thickness	Depth	Breadth
Section 30	Vertical	1·2 - 1·45	30	12
	Vertical	0·7 - 2·3	12	7
Section 29	Vertical	2·1	10·5	6
Section 34	60°	1 0	18	8
Section 3	Vertical	2·2	11	3·5



a Spreitichnus. Vertically disposed specimen in calcareous sandstone, section 30. Note fan shaped radial grooves and warts. (x0·5)

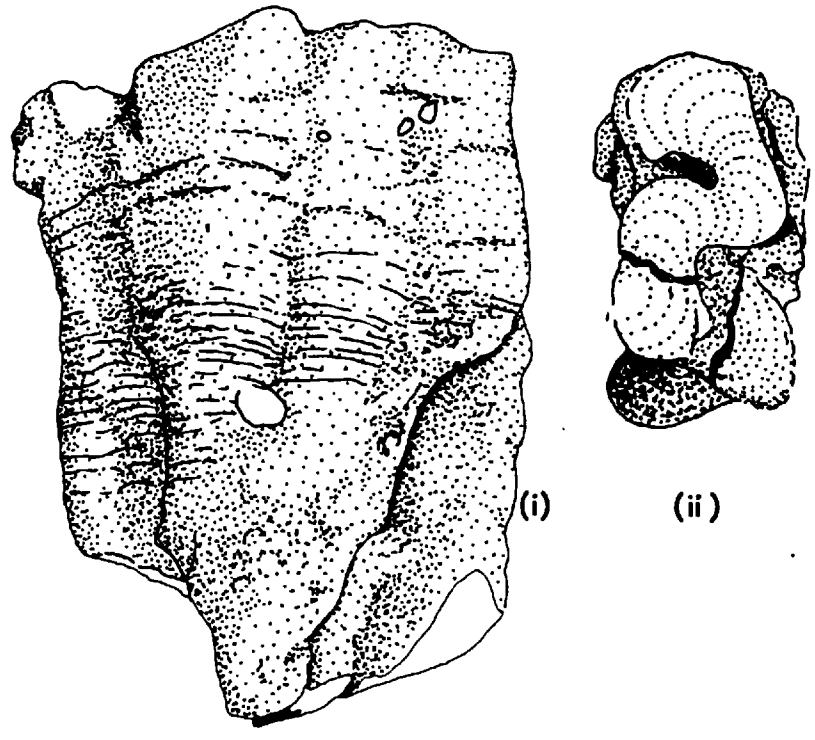


b Spreitichnus. Top view of specimen above. Note thickness and sideways meniscus fill. (x0·5)

Figure 4.8

Geographic distribution: These burrows occur in calcareous sand - stones and interlaminated sands and shales and are closely associated with other burrows especially Caegichnus, Ophiomorpha and Capsites.

Interpretation: The meniscus fill indicates that they were created by a deposit feeder that systemmatically reworked one side of its original burrow throughout the whole length, and repeated this pro - cess until a large sheet-like sand filled body was built up. Seemingly it burrowed one end more vigorously than the other in specimens that are not exclusively vertical, and eventually produced a fan shaped struc - ture. The meniscus structure shows that there was active back-fill of sediment into the excavated portion throughout the period of burrowing. The general form of the burrow resembles Teichichnus Seilacher 1955, a vertical fexuous spreiten Fodinichnia burrow with however, a horizontal meniscus fill.



a Spreitichnus. Vertical specimen in calcareous sandstone. Section 29
(i) Lateral view (x0·5). Note traces of bedding on surface
(ii) Bottom view (x0·5). Note meniscus fill.



b Corophiodes. burrows in sandy limestone. (x1) Section 34



c Horizon in calcareous sandstone at section 33 highly burrowed by Corophioides. Scattered Aestites are present as well.

Figure 4.9

Corophioides Smith (figure 4. 9 b,c)

Description: These consist of small unbranched U-shaped sand filled burrows in which the tubes are 0·15 cm to 0·4 cm in diameter and about 0·4 cm apart. Thin silty sand interbeds are affected, the depth of burrowing depending upon their thickness, being between 3 and 6 cms (figure 4. 9b).

A very thin 0·025 - 0·05 cm thick silty wall is present, and this is manifested around the aperture by a low elevation. In calcareous sand beds the aperture appears as a low mound 0·4 cms diameter (photo 4. 2a)

Though most of the specimens are regularly U-shaped, many are not, meandering considerably from the vertical and even having apertures touching or up to 1·5 or 2 cms apart (figure 4. 9b).

The burrow has a restricted distribution, but is remarkably ab - undant where it occurs. It is best developed in the finely interlaminated rippled sands and shales of a strongly discordant channel at section 39. Throughout the unit for at least 15 metres there is an alternation of dominantly sandy beds 15 cms thick and dominantly shaly beds 30 cms thick dipping constantly 12° to the southwest. The burrows are best developed in the sandy portion where the concentration reaches 48,000 per square metre in particularly well burrowed horizons. In most inter - beds burrowing is vertical or perpendicular to the surface (i.e. dipping 12° from the vertical), but in many cases down dip slipping has occurred. This results in the burrows being lengthened and gradually pulled over, so that at the top of the interbed they dip 60° away from the vertical. Burrows from the interbed above pass down into the affected part undis - turbed, showing that the slipping occurred before deposition of the latter. There is a tendency for the axis between the limbs of the burrow to be oriented parallel to the strike of the dipping channel sediments (figure 4. 10a).

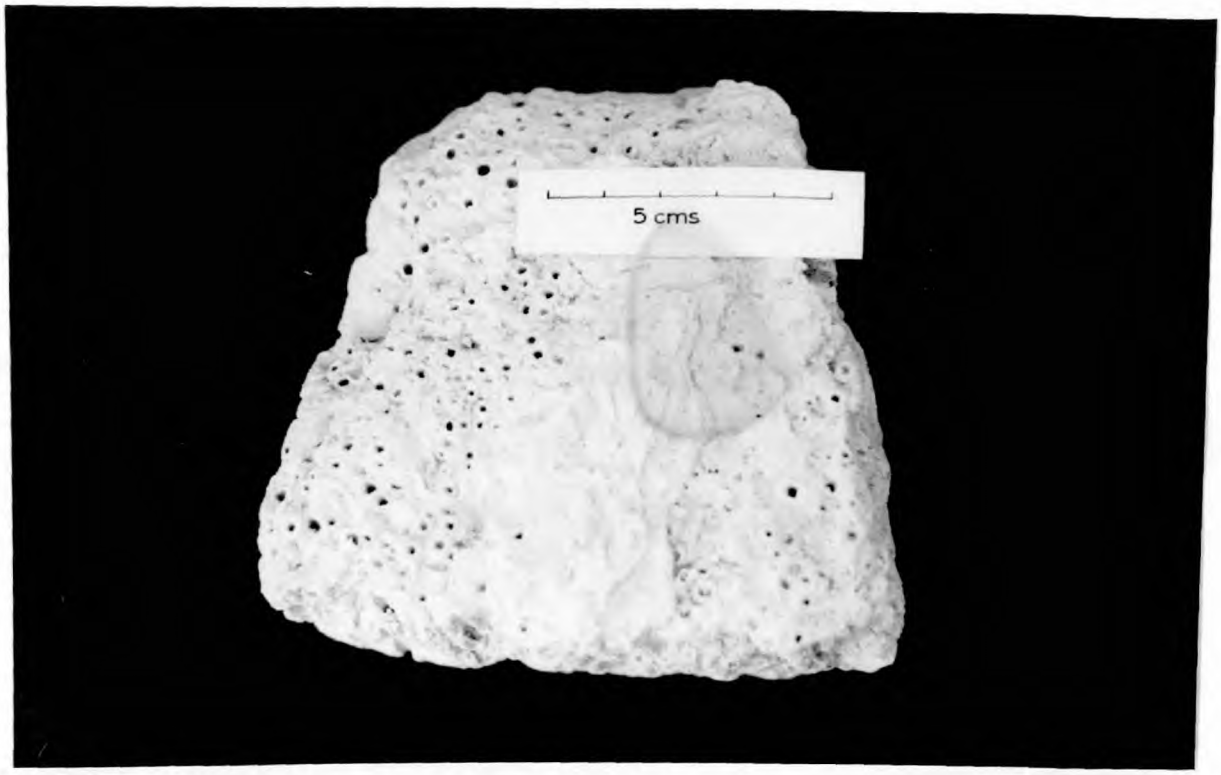


Photo.4.2a. Top surface of Corophioides - burrowed interlaminated sand and silt. Note concentration and low rings around apertures. From tidal channel point bar deposits at section 39.



Photo. 4.2b. Vertical section through muddy sand with burrows of Corophium volutator. Tidal lagoon at Gibralter Point, near Skegness, Lincolnshire.

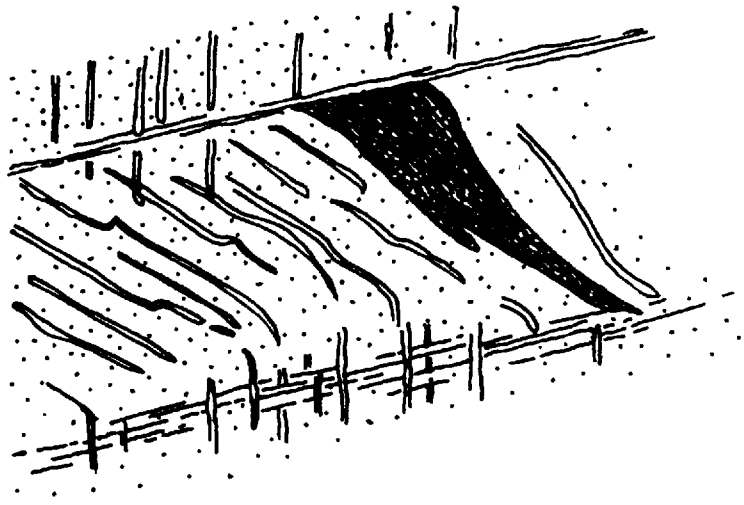
At section 33 a single level in a calcareous sandstone is very highly bioturbated by this form over an area of over 50 metres of outcrop. (figure 4. 9c).

Geographic distribution: Corophioides is restricted to the cal - careous sandstones of the south side of the Jebel Zelten.

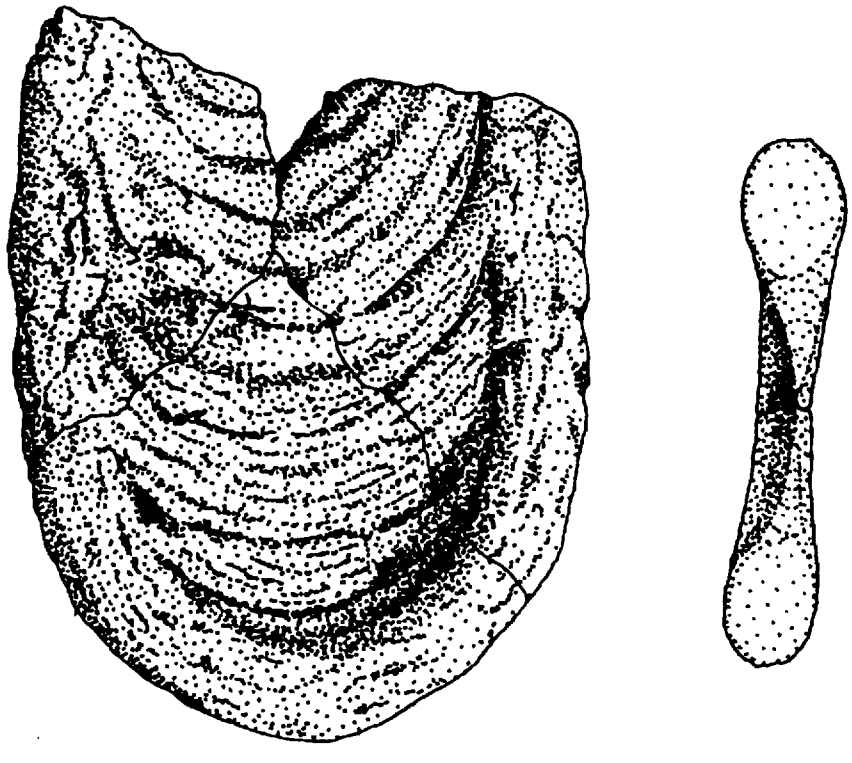
Interpretation: The burrows are identical to those produced at the present day by Corophium volutator Pallas, in the tidal creeks and mud flats of the North Sea intertidal zone (photo 4. 2b). Particular features in common are the thin mucus-cemented casing, the irregularity of some of the U burrows, and the depth and concentration of burrowing. On a mud flat at Gibraltar Point, Skegness, 18,000 Corophium volutator were counted in an area of 1 metre by 10 cms deep. They were presumably largely or wholly represented by burrows. The highest figure for con - centration of Corophium volutator is that of Watkin (1941) who recorded 63,000 young per metre^2 in the Dovey Estuary (in May). From their dis - tribution along the Norfolk and Lincolnshire coast it is clear that the animal prefers a mixed muddy and sandy substrate, rather like the interlaminated beds of the Zelten region, probably in salinities of about 30°/oo.

Lessertisseur (1954) and Seilacher (1967) noted that some Corophium volutator burrows have spreiten, representing downward migration in the sediment (as with Diplocraterion). The spreiten are, however, extremely diffuse and invisible unless impregnated carefully (Reineck 1967). The chances of preservation in the dominantly sandy beds at Zelten are not considered good enough to warrant their use in classification.

It is concluded that the burrows were Domichnia of Corophium volutator or a closely related Corophium sp. and represent an intertidal channel and muddy sand flat environment such as those present on the North Sea coast today. The salinity may have been slightly lowered, in the region of 30°/oo, and the depositional rate was probably slow.



a Vertical face of interlaminated sand and shale at section 39 showing downdip slipping pulling Corophioides over. (x 1)



c Diplocraterion yoyo Goldring. Side view of a protrusive form showing longitudinal striations on arms and semilunar ornament on the spreiten. Cross section on right shows dumbbell shape and meniscus fill in spreiten.
(x1) Section 32.

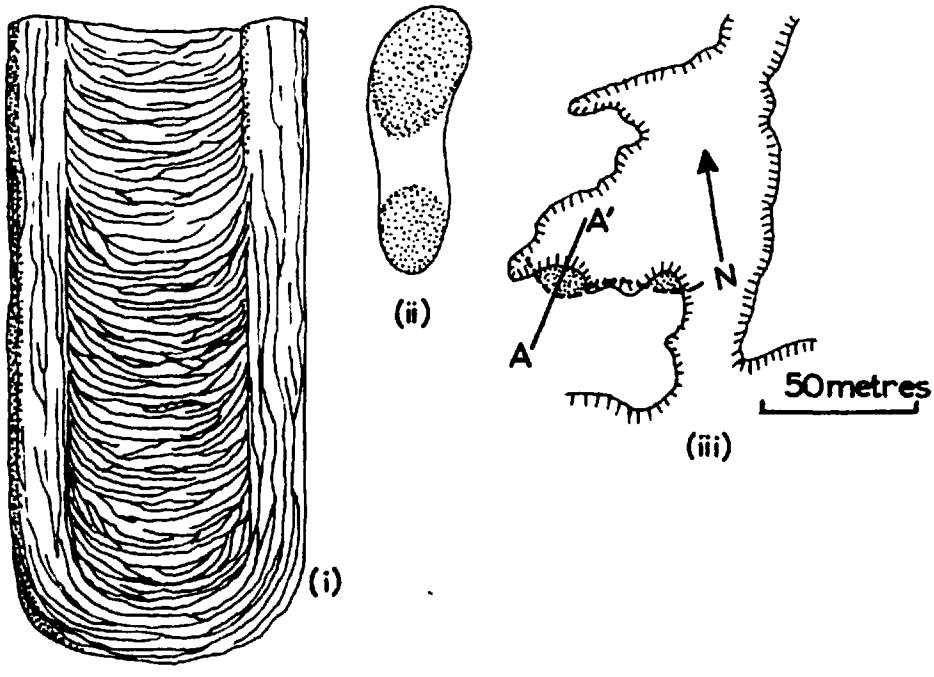
Figure 4.10

Diplocraterion yoyo Goldring (figures 4, 10,11,12,13)

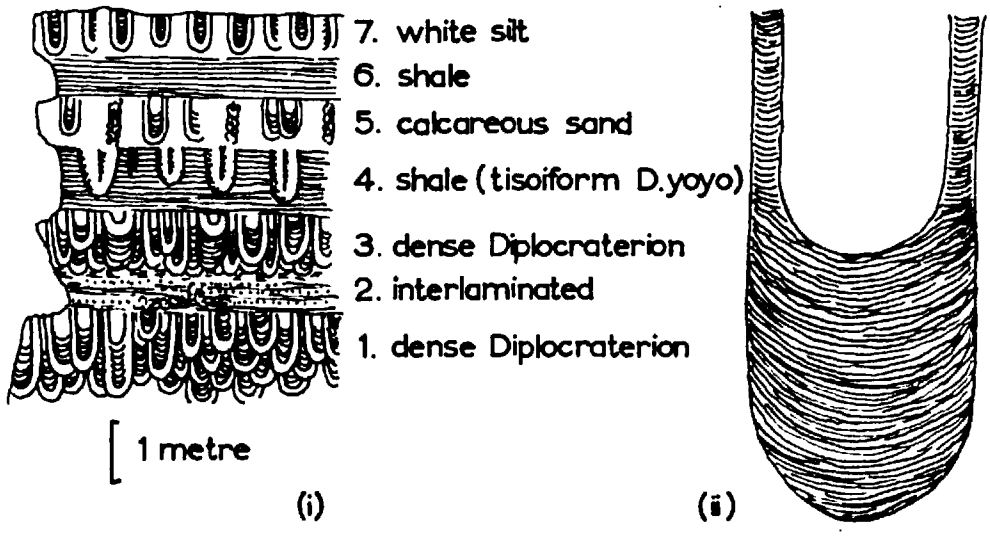
Description: Diplocraterion burrows consist of vertical U-shaped tubes varying in size from 3·5 cm across and 12 cms deep, to 8·5 cms across and 45 cms deep with spreiten (the septum of Goldring 1962) associated with the lower part of the vertical components.

The U is composed of two parallel cylindrical vertical arms 1·8 to 2·0 cms in diameter joined at their bases by a convex-downward horizontal member of the same diameter. The distance between the vertical arms is usually between 5 and 6 cms but in small specimens it may be only 2 cms, and in large specimens it may reach 8 cms. In one specimen the arms converge towards the top, so that the distance between them decreases upwards from 4·5 to 2·7 cms. The outer surfaces of the tubes are ornamented with longitudinal striations and sharp anastomosing ridges 0·2 cm high and up to 10 cm long (figure 4. 10 b).

The spreiten is normally within the U burrow forming a protusive form (Goldring 1962) and consists of a series of shallow semilunar components of the same trend but without the vertical arms. The thickness is usually about one half that of the U tube, resulting in the dumbbell cross section discribed by Goldring (1962). In a calcareous silt (section 36 unit 7), however, all the examples have spreiten of equal thickness to the tube so the cross section is sausage-shaped (figure 4. 11.). In some specimens there is a gradual downward increase in the thickness of the spreiten. Most specimens have spreiten composed of large irregular wrinkles about 2 cms thick, the surfaces of which are covered with anastomosing semilunar striations and ridges - the septal laminae of Goldring - as on the vertical tubes. When the sediment fill is silty, the spreiten is often picked out by thin laminae of sand containing irregular 0·1 cm diameter silt balls, probably representing faecal material.



a (i) Diplocraterion yoyo. Protrusive form with well developed ridges (x0·5) Section 36 unit 7.
(ii) Transverse section of (i) showing sausage shape.
(iii) Plan of distribution of D. yoyo in unit 7 along wadi wall. Note east-west elongation. A-A' = orientation of long axes



b (I) Section of Diplocraterion bearing rocks at section 36. Note the proximity of tisoiform types to normal types.
(ii) Vertical section of a retrusive specimen of D. yoyo showing concave-upward fill. (x 0·25) Section 36 unit 3

Figure 4.11

Complete 45 cm deep burrows contain spreiten through between a third and two thirds of their depth, the top 15 to 30 cms represented only by the parallel vertical arms. A few specimens in which the spreiten is outside and below the U-tube - the retrusive form of Goldring 1962, occur together with protrusive types in section 36 units 1 and 3. Half of the depth (45 cms) is composed of spreiten of the same thickness as the vertical arms (figure 4. 11 b(ii)).

Most specimens are filled with sand and structures both within and on the surface of the burrow are obscure. However, a horizontal meniscus fill in the vertical arms is common and in cross section this appears as a concentric lamination around a central tube.

In units at the base of section 36 bioturbation by Diplocraterion is most concentrated. Along an outcrop of at least 200 metres 50 burrows per metre^2 occur to the exclusion of everything else. In two of the units, each interlaminated sands and shales 70 cms thick, vertical sand-filled Diplocraterion with 0·3 cm thick concentrically patterned walls are progressively eradicated by those above. Specimens in the top 45 cms are less interrupted than those below and in large part re - present the final population.

Visually the units may be divided into 3 (photos 4. 3ab, 4a)

(a) a basal zone (25 cm) of repeatedly cut out U-tubes and spreiten.

(b) a central zone (20 cm) of U tubes and spreiten belonging to the final population.

(c) a top zone (20 cm) of vertical tubes, separated by host rock silts and sands.

Nearly all of the burrows are protrusive, only a few retrusive forms being present.

In unit 7, a dense white calcareous silt 30 cms thick, 80% of unwalled protrusive Diplocraterion burrows (12 to 21 cms deep and 6 to 9 cms across) are oriented with the axis between the limbs of the U tubes

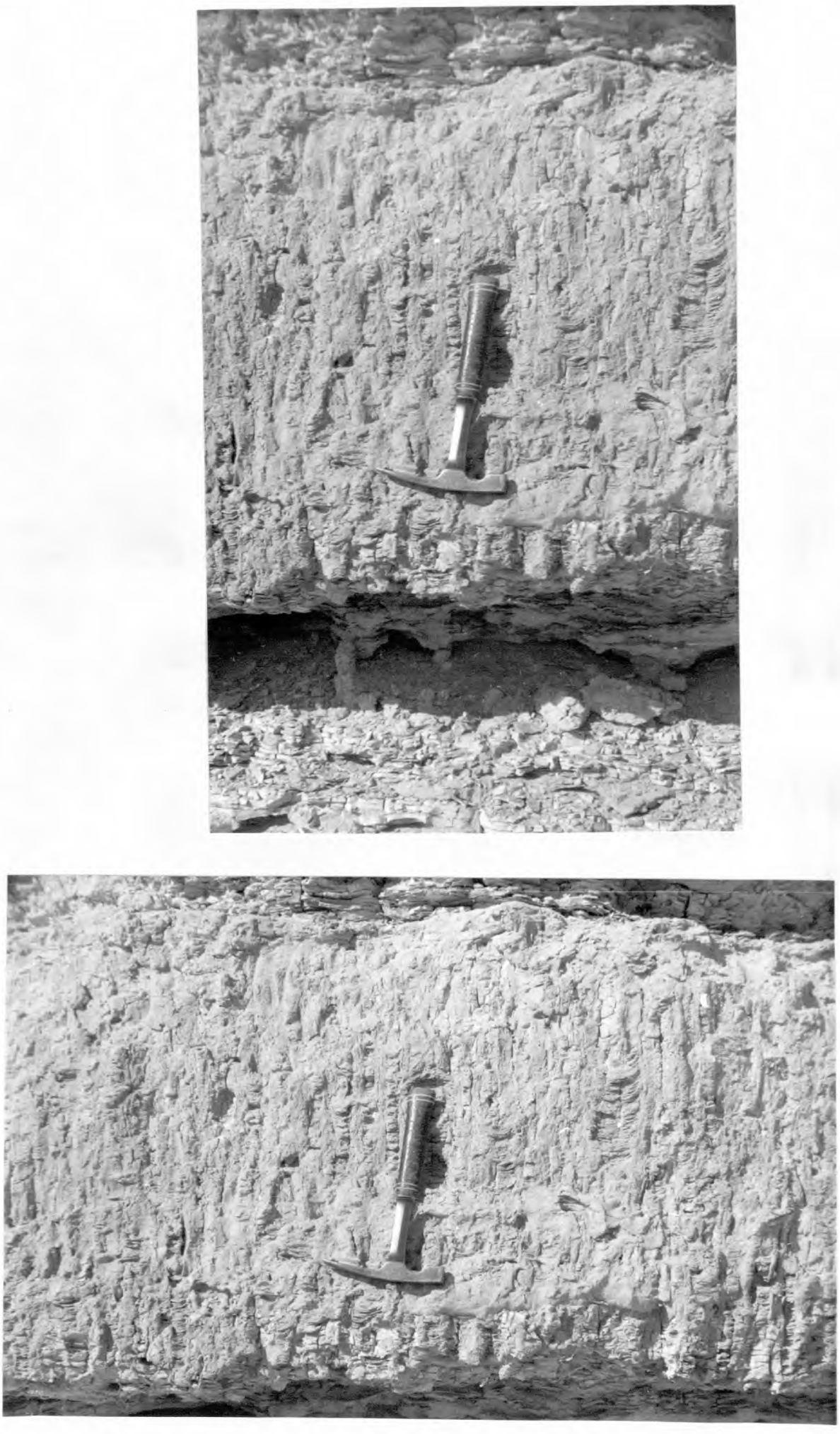


Photo. 4.3. Vertical face of Diplocraterion - burrowed calcareous sand and shale at section 36 unit 3

30° east of north. Commonly the spreiten is as thick as the U-tube and is about 13 cms deep, and present throughout the shallower specimens. Their distribution in the unit is limited to an elongate zone of 50 metres more or less east west (figure 4. 11a(iii)).

Geographic distribution: Diplocraterion is restricted to the calcareous sands on the south side of the Jebel Zelten.

Interpretation: Goldring (1962) interpreted the protrusive and retrusive behaviour of Diplocraterion yoyo from the Baggy Beds as an accomodation to changes in the sedimentary surface - the former related to erosion and the latter to deposition, supposing the original burrow to be a simple U-tube without spreiten. In the Zelten specimens pro - trusive forms are very dominant, even in units in which there has clearly been net deposition (section 36, units 1 and 3). To account for this it seems likely that a downward migration of the burrow was a normal part of the life history of the animals that produced the Zelten specimens. Thus protrusive forms would be produced during both stable conditions as well as rapid erosion, while retrusive forms would only be produced by rapid deposition. Systemmatic upward or downward migration through the sediment is similar to the behaviour typical of deposit feeders (figure 4. 13).

Tisoiform types

Description: In shale units closely associated with occurences of Diplocraterion yoyo, U-shaped burrows without spreiten are found. They consist of a sand filled tube doubled back upon itself, the arms of which are closely applied to one another. They are each 5·0 to 6·0 cms in diameter and 30 cms deep, though short examples seem to increase in diameter upwards (figure 4. 12(i) and photo 4. 4b).

An irregular concentric lamination seen in cross section persists down the vertical arms and around the base and is brought out by layers alternately richer and less rich in silty or ferruginous silty material

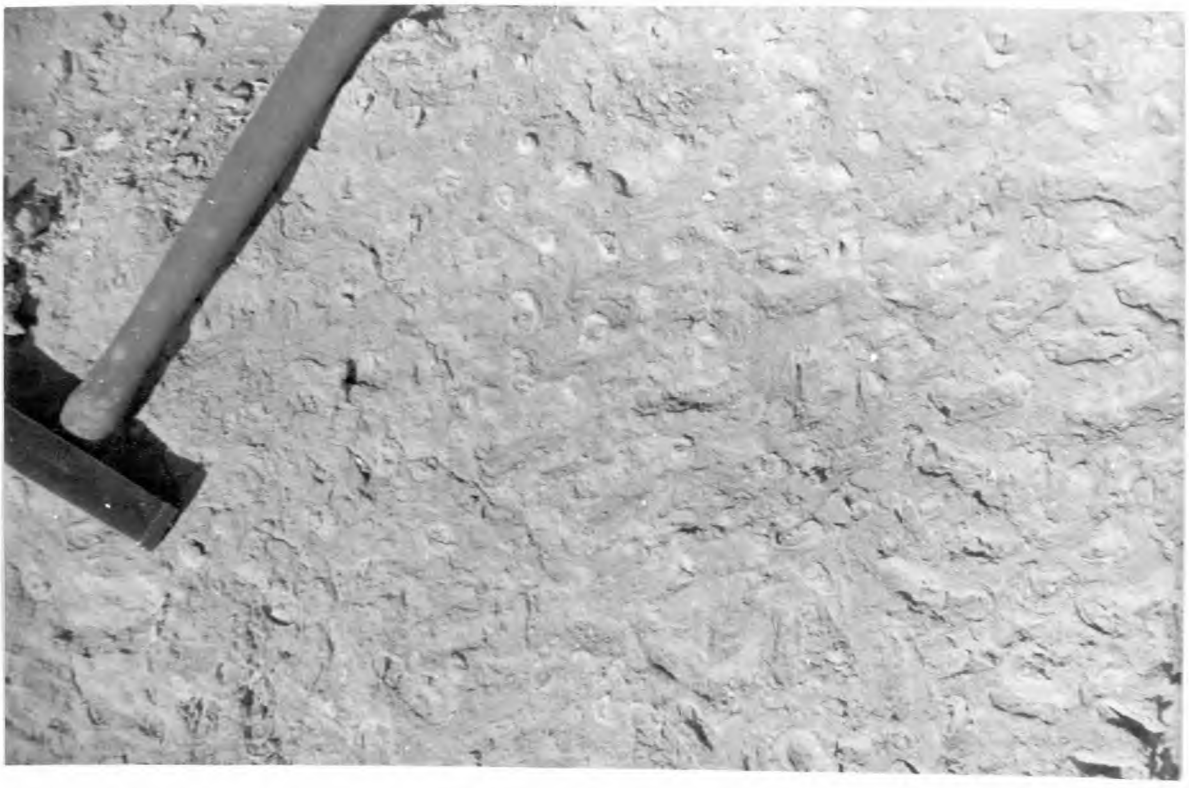


Photo. 4.4a. Top surface of Diplocraterion - burrowed sand, showing separate pairs of vertical arms (left) and pairs joined by spreiten (right) . Section 36 unit 3.

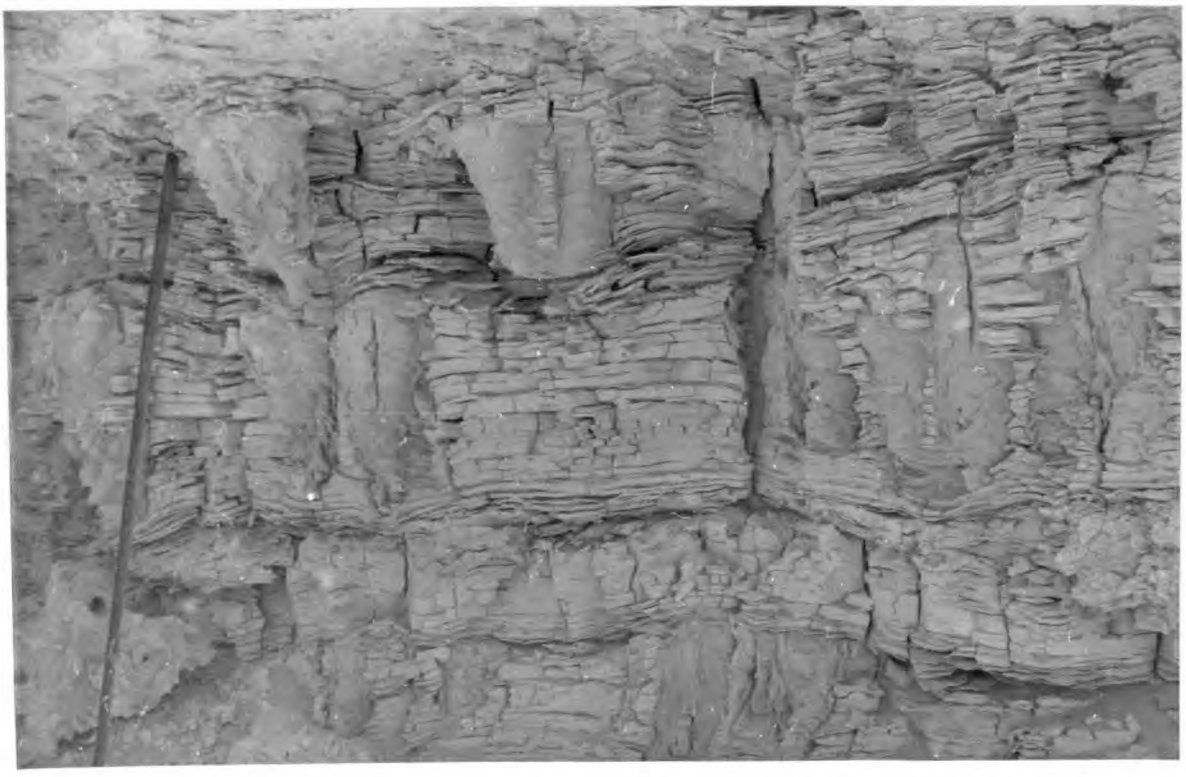
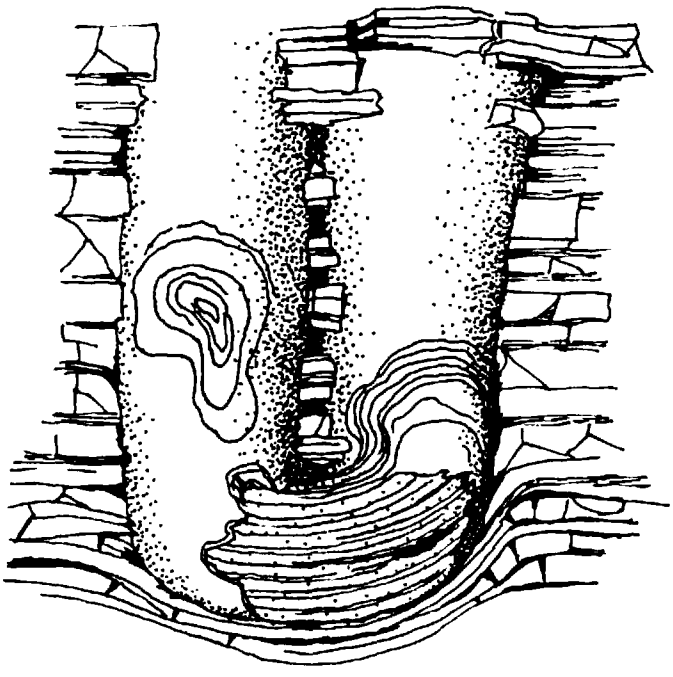
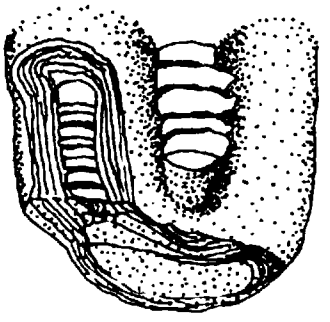


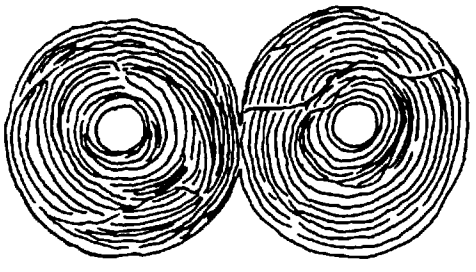
Photo. 4.4b. Tisoiform Diplocraterion in shale unit. Section 36 unit 4.



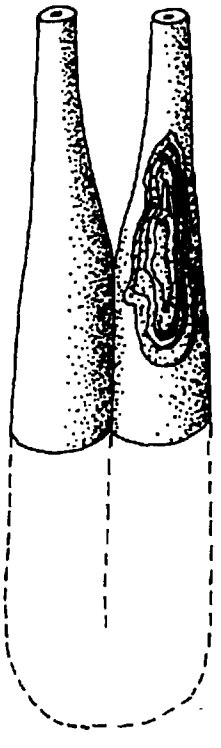
(i)



(ii)



(iii)



(iv)

Tisoiform Diplocraterion
Section 36 unit 4

(i) Specimen in shale. Note concave upward fill in horizontal portion and concentric fill in arms. (x0·3)

(ii) Oblique underview of specimen with a silt filled central tube. (x0·25)

(iii) Top view of specimen showing interrupted concentric fill and silt filled central tube. (x0·3)

(iv) Complete specimen showing gradual convergence of arms (x0·1)

Figure 4.12

(figure 4. 12 (iii)). A central sand or silt filled central core 1·3 cm in diameter is often present (figure 4. 12(ii)).

One specimen 12·5 cm across the top is 60 cms deep and increases gradually in size downwards, so that at the base it is 20 cms in diameter. At the top the two arms are 4·5 cms apart and 4 cms in diameter, but they become more and more closely associated downwards and meet 30 cms from the base. Their diameter increases to 10 cms so that the outer profile of the burrow remains more or less in a straight line. This specimen being much larger than any of the others probably represents a complete specimen. All of the others have probably been truncated by erosion (figure 4. 12(iii).

Interpretation: The similarity in size and structure between these U-shaped burrows and the figures of Tisoa siphonalis de Serres, in Lessertisseur (1955) and Gottis (1954) - especially pl XXVII figs 6,9,11, is marked. The large calcareous structures from the middle Lias of the Rhone and the Oligocene of Tunisia were noted by Dumortier (1869) to be joined at the base. The calcareous concretions around many specimens are clearly secondary additions to the structure since many specimens do not have them (see figures of Gottis 1954). Karaszewski (1967) for instance noted such concretions forming around Diplocraterion burrows in the Aalenian of Poland.

The sizes and behaviour of these burrows indicate a relationship with Diplocraterion yoyo, in which as has been suggested, a simple U-shaped tube produces spreiten during both its normal life activity and as a response to erosion and deposition. In fine-grained substrates, where the stability of the sediment is much greater than in interlaminated sands and shales little erosion or deposition takes place and the nec - essity for upward or downward migration is reduced. The sediment is rather richer in organic material so the animal excavates the walls to feed rather than migrating downwards. The end product of this behaviour

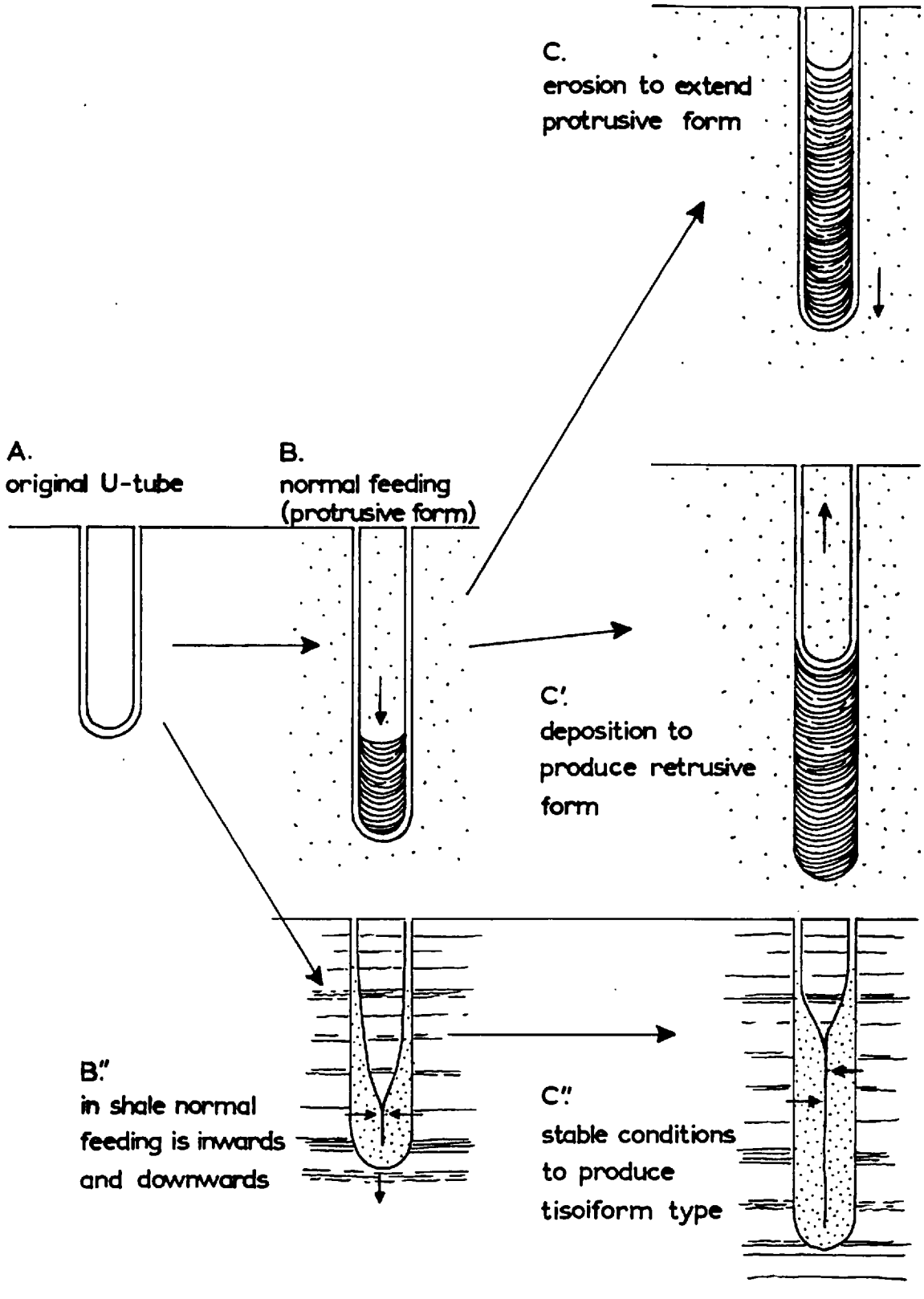


Diagram to show interpretation of events leading to the various forms of Diplocraterion.

Figure 4.13

pattern is a U-shaped burrow in which the tubes are so large that they are in contact with one another (figure 4. 13).

The similarity between the dimensions of these specimens and the Diplocraterion present in the adjacent units suggests that the animal burrowed inwards only. The central silt-filled tube with associated concentric lamellae indicates that constant re-excavation of the burrow took place. Exactly the same structure was noted by Abel (1935) and by Goldring (1962) in the apertural funnel of Diplocraterion yoyo. Reineck (1950) observed concentric lamination in the burrow walls of Nereis and Mya in the recent sediments of the North Sea.

It is concluded that both Diplocraterion yoyo Goldring and possibly also Tisoa siphonalis de Serres, are present, and represent different behaviour patterns produced by the same animal burrowing in dominantly sandy and dominantly silty and shaly substrates, respectively. For the purposes of this study the latter are termed tisoiform Diplocraterion, as there seems to be some doubt as to the diagnosis of Tisoa siphonalis (Hantzschel 1962). Elongate ridges and anastomosing striations on the outer walls of the U-tube suggest that both types were formed by crus - taceans, possibly quite closely related to those producing Ophiomorpha and Thalassinoides.

The frequent indications of erosion and deposition in the beds in which they occur, coupled with the interbedding of sand and shale units suggests that they were formed in very shallow water or intertidal en - vironments. The crowding of units by Diplocraterion at section 36 re - calls the kind of dominance noted by MacGinitie (1935) for species of crustacea in small patches of the Californian estuary, Elkorn Slough. The patchy distribution of Diplocraterion is possibly due to the local - isation of optimum conditions for the development of the burrower - a feature most likely to be met with in an intertidal or estuarine environment where there are rapid fluctuations in depth, temperature

salinity and current activity.

Vertical U-shaped burrows with spreiten have been described from 30 to 35 metres depth in the North Sea by Reineck, Gutmann and Hertweck (1967) - the work of Echinroid worms. They are, however, rather ir - regular and only resemble Diplocraterion in general form .

The orientation of the specimens in section 36 unit 7 suggests that there was a tendency for the axes between the arms of the U to be oriented at right angles to the long axes of the distributions, perhaps an accomodation to water currents.

Diplocraterion burrows fall into the category of Fodinichnia of Seilacher (1964).

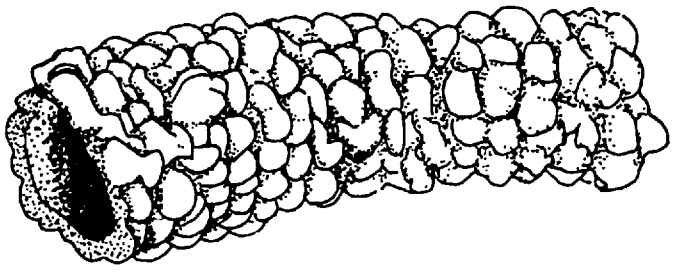
The Ophiomorpha group (figures 4. 14,15,16)

This includes a number of burrows of differing size and form that are interpreted as being closely related. They are divisible into two groups depending upon whether they have a wall or not.

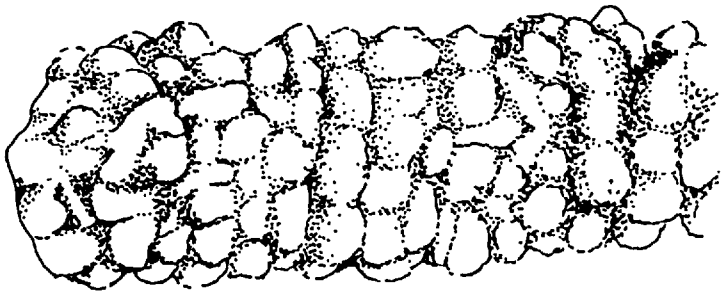
A) Ophiomorpha Lundgren

Description: These comprise branching tubular bur - rows, 0·5 cm to 11·0 cms in diameter, disposed vertically and horizontally. They are characterised by an 0·2 to 1·8 cm thick wall composed largely of host rock sand grains in a more or less calcareous silty or limonitic matrix. The outer surface of the wall is covered with circular or trans - versally elongate warts or pustules divided by deep clefts. They have a relief about two thirds of their diameter and are arranged in irreg - ular transverse rows. At their bases, the warts merge to form a compact cylinder - the wall, which has a smooth internal surface with a slight transverse wrinkling. The central tube is 0·4 to 3·2 cms in diameter and is commonly filled with unconsolidated sand. A meniscus structure is occasionally present. The burrows correspond closely to Ophiomorpha Lundgren. Graphs plotted on a random selection of measurements of the external diameter show that 3 distinct size types are present.

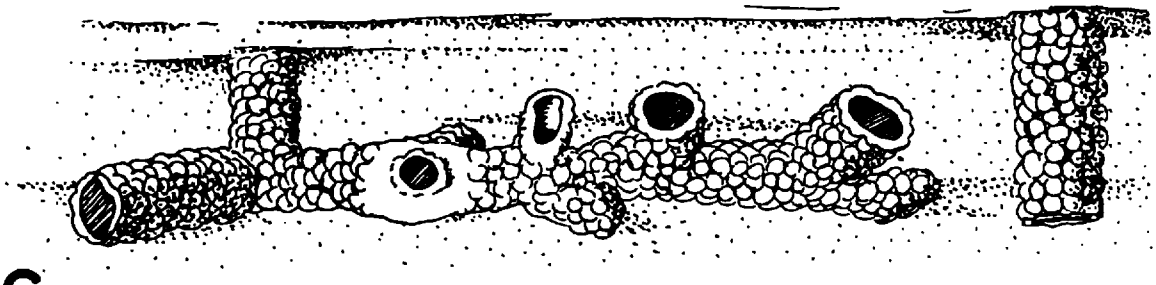
(i) The smallest, which vary from 0·5 cm to 1·7 cm in diameter, but are usually 1·3 cm in diameter, and are of rather low relief. The burrowing pattern, which is best seen in sands, comprises rather ir - regularly meandering and frequently branching vertical and inclined forests and horizontal plexi producing complexus up to a metre thick. Upwardly directed components, ending blindly or branching dichotomously or polychotomously arise from the horizontal. Burrows both turn through 90° and branch to produce this, the result often resembling an upwardly cupped hand. The branching is usually 90° and the internodes between 4 and 6 cms long.



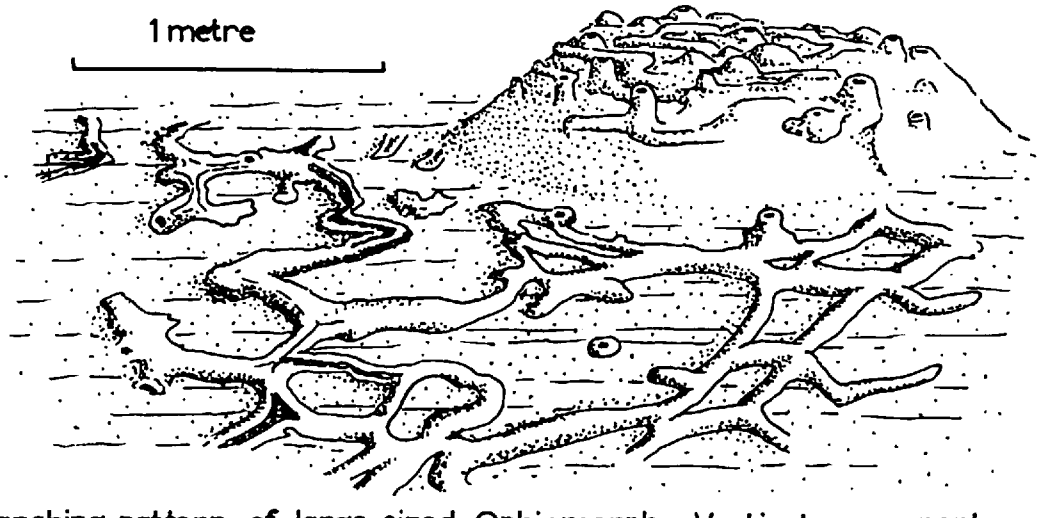
a Medium sized Ophiomorpha Lundgren with a thick wall composed of irregular transverse rows of warts (x1·5) Section 16



b Large sized Ophiomorpha Lundgren with rather more diffuse warts. (x1) Section 23



c Medium sized Ophiomorpha burrow system in calcareous sand (x0·5) Section 4



d Branching pattern of large sized Ophiomorpha. Vertical components pass down to a level with a horizontal plexus. Section 5

Figure 4.14

(ii) Medium sized Ophiomorpha burrows, between 1·7 and 3·6 cms in diameter (average 2 5 cms), have an 0·2 to 0·5 cm thick wall. The warts are 0·4 to 0·6 cms in diameter and are arranged, as before, in transverse rows that are often incomplete or interrupted by compound warts. The burrow pattern is very much more simple than in the smaller variety, consisting of a straight vertical or high angled tube up to a metre long, joined at various levels to horizontal or low angled straight or meandering branching systems. A concentration of 1 vertical tube per 20 cms of vertical section is typical, each with 2 or 3 radiating horizontal branches from which short horizontal and vertical components arise. The branching is 90° and the internodes vary from 7 to 25 cms long (figures 4. 14a,c).

(iii) The largest Ophiomorpha burrows vary from 3·6 to 11·0 cms in diameter, and have a variably thick case. The central tube is usually about 3·0 cms in diameter, but may not be clearly differentiated from the wall due to partial cementation of the sand grains within it. The warts, which are between 1·0 and 1·5 cms in diameter occur in trans - verse rings of diminishing size at blind endings. Simple vertical com - ponents up to 50 cms long and depressed horizontal tubes are typical, but at section 5 a surface of calcarenite shows the complete pattern. 4 cm vertical tubes of calcareous silt within thick calcarenite walls pass downward to a horizontal plexus of anastomosing components. Below this level there are vertical tubes only again and they gradually dec - rease in diameter to 2·5 cms in 40 cms, and die out (figures 4. 14b,d).

(iv) A modification of the straight horizontal components of the medium sized Ophiomorpha burrows found in sands with thin silty inter - laminae, is characterised by the partial loss of the warty wall. At section 16 typical round or elongate 0·5 to 0·8 cm diameter warts, ar - ranged as usual in transverse rows across the burrows are absent from

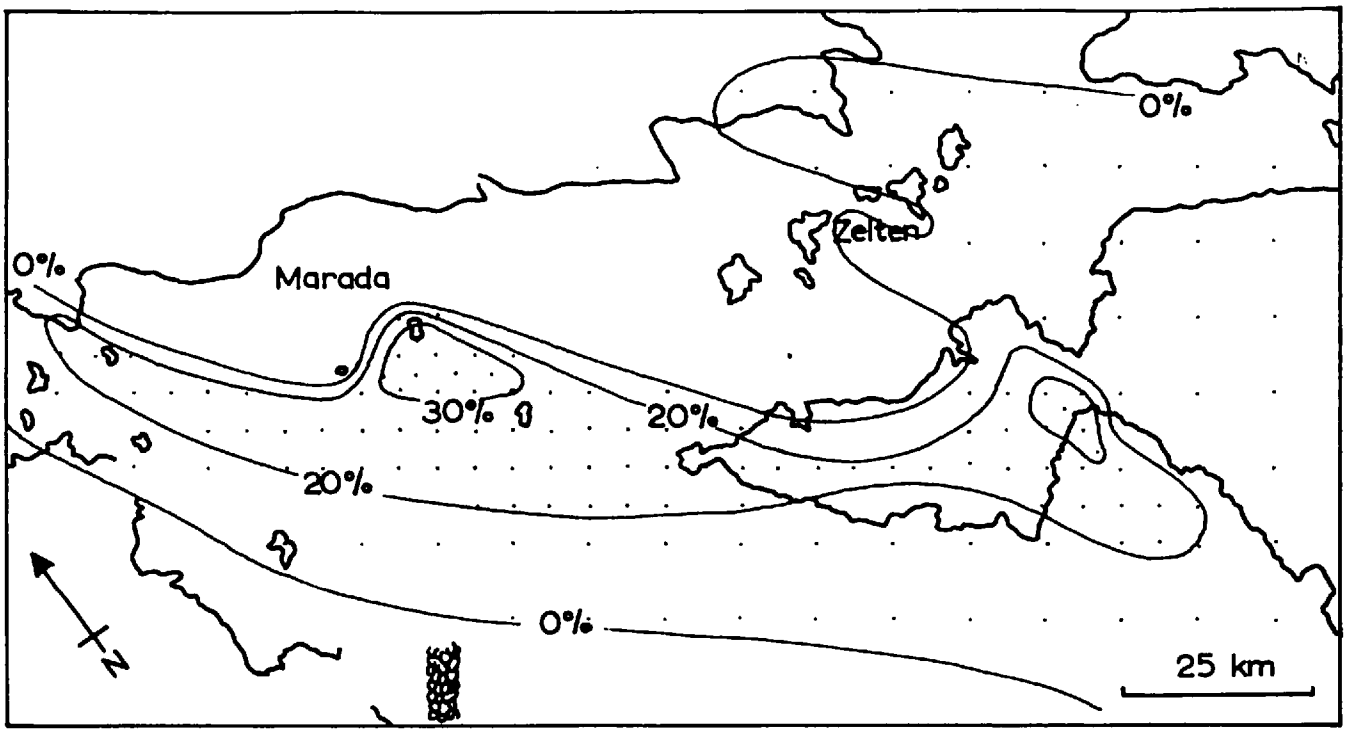
the bottom in an arc varying from 50° - 130° of the circumference. Towards the bases of the sides, normal sized warts 0·8 cm in diameter form the whole of the wall, no compact cylinder being present. There is a sharp boundary to the bottom part where there is no wall. Thin 0·1 cm diameter silt interlaminae are often incorporated into the warty part of the wall and the burrow is nearly always depressed (e.g. 3·0 x 2·0 cm diameter). Elongate ridge marks are present in many specimens on the unwalled part (figure 4. 16a(i)). At a section 600 metres east of section 7 and at section 30 specimens with only a single row of warts along the bases of each of the sides are seen, and mark an almost total reduction of the wall (figure 4. 16a(ii)).

Geographic distribution (figure 4. 15a): Small and medium sized Ophiomorpha burrows normally occur together and their distributions have been considered together. They are found in 105 units, mainly interlaminated sands and shales and calcareous sands. They are commonly associated with Needleichnus and Caegichnus burrows, but also occur with Thalassinoides, Premorites and Alukichnus. Marine fossils are found in 34% of the units, and belong to the bivalve-gastropod, Crassostrea gryphoides, Callianassa and ribbed bivalve biofacies. These all indicate shallow water or intertidal brackish or marine environments.

Large Ophiomorpha burrows are found in 10 units, nearly all calcareous sands and interlaminated sands and shales. They are nearly always associated with other burrows, usually Needleichnus or other Ophiomorpha burrows and Thalassinoides. In 60% of the units marine fossils occur and once again the environments indicated are shallow water and intertidal, fully marine to brackish.

Ophiomorpha with partially reduced walls is only found in 4 units, always sands with thin silty interlaminae. It is always associ - iated with small and medium sized Ophiomorpha burrows.

a Percentage distribution in sections of small and medium sized Ophiomorpha



b Percentage distribution in sections of medium sized Thalassinoides

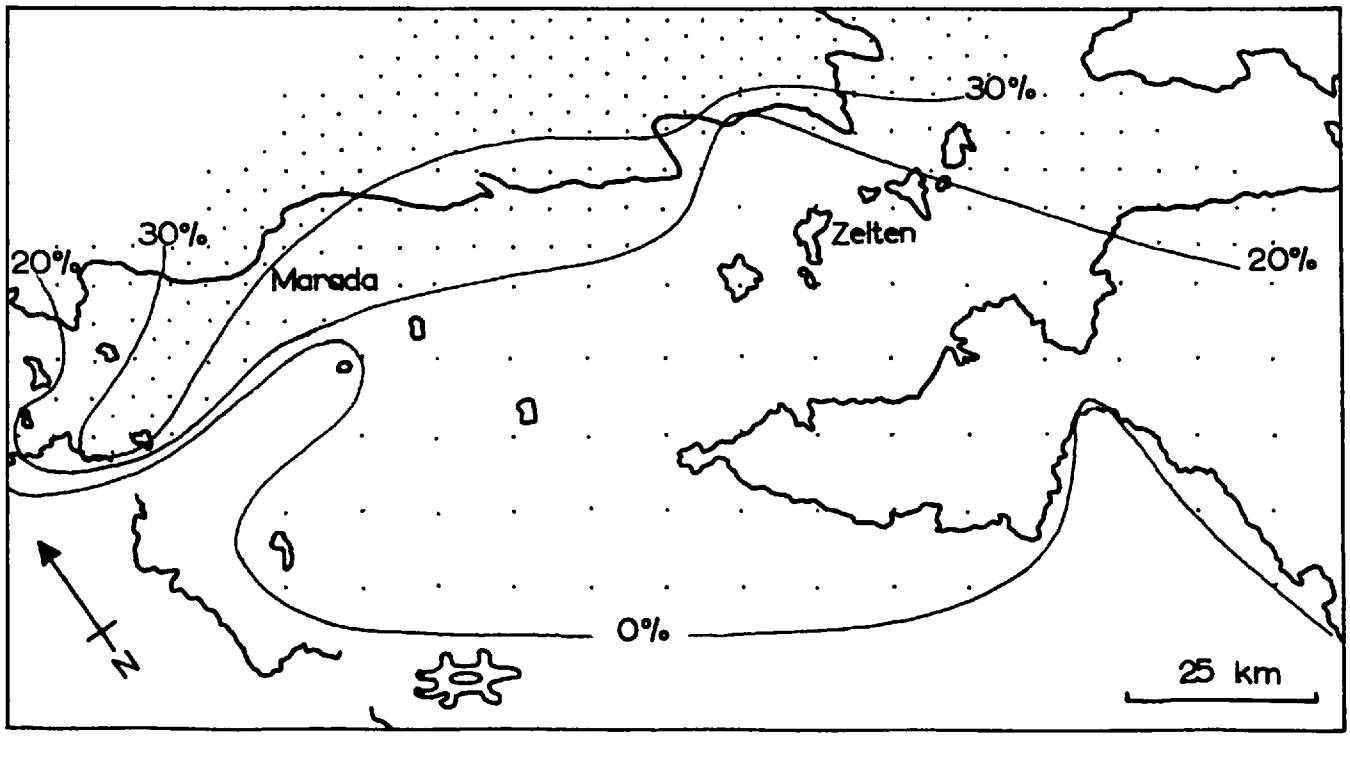


Figure 4.15

B) Thalassinoides

Thalassinoides burrows consist of unwalled sand filled tubes, rather irregular in diameter, that branch Y-fashion very fre - quently. The surface of well preserved examples of medium sized types is ornamented with irregular anastomosing ridges up to 0·4 cm long and 0·1 cm high, or low rounded lumps (figure 4. 16c(i)). As with Ophiomorpha three size types are recognised.

(i) The smallest, between 0·5 and 1·5 cms in diameter (mainly 0·9 cm in diameter) consist of short vertical sand filled tubes with Y-branching horizontal components arising at one or more levels to pro - duce close-knit polygonal plexi. They nearly always burrow into shales or silty shales from the base of a sand unit or from a sandy interlamina in a shale. Horizontal plexi occur every 3 or 4 cms below the horizon from which the burrows originate, and 60% or 70% of the bed may be bioturbated for a depth of 10 cms or so. Internodes are rarely more than 2·5 cms long.

(ii) Medium sized Thalassinoides, between 1·5 and 3·5 cms in diameter are very similar to the small types but burrow deeper and are found in sands as well as shales. Vertical pipes up to 60 cms deep, but mainly between 10 and 30 cms deep give rise to horizontal plexi every 6 or 8 cms (figure 4. 16c(ii)). Internodes are usually about 8 cms long, and irregular swollen areas are often seen at the nodes. As in the case of the smaller types 60% or 70% of the bed may be bioturbated, but in some cases the whole sediment has been reworked several times. Shale units affected by this process are almost completely replaced by infillings and are represented by sands with a few residual blebs of shale near their bottoms (figure 4. 16b(ii)).

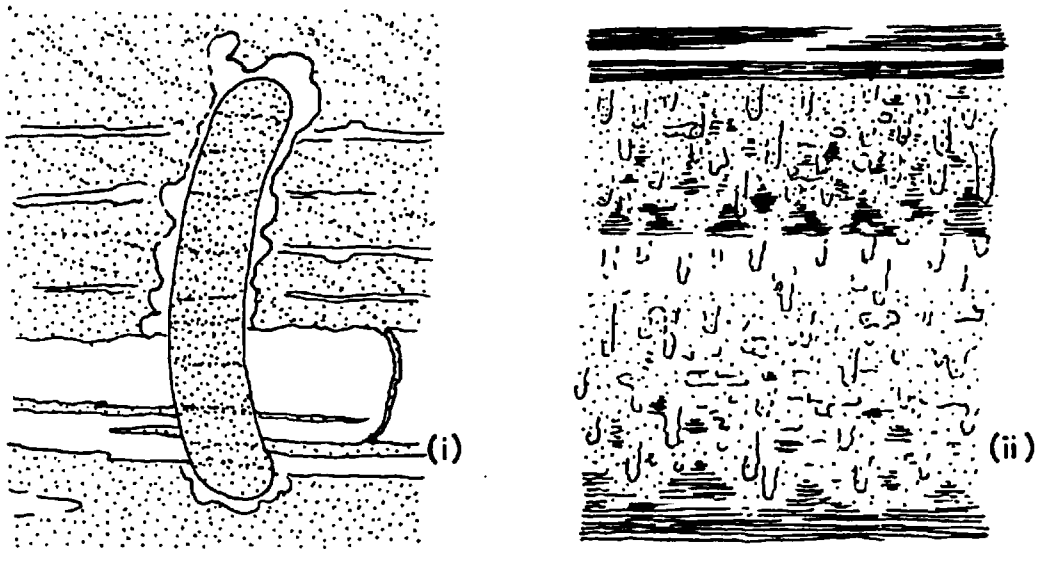
In some interbedded sand and shale units this type and the medium sized Ophiomorpha occur together, and in one or two cases may be seen



(i) (ii)

a (i) Ophiomorpha with partial loss of the warty wall. Oblique underview of horizontal component. (x1) Section 16.

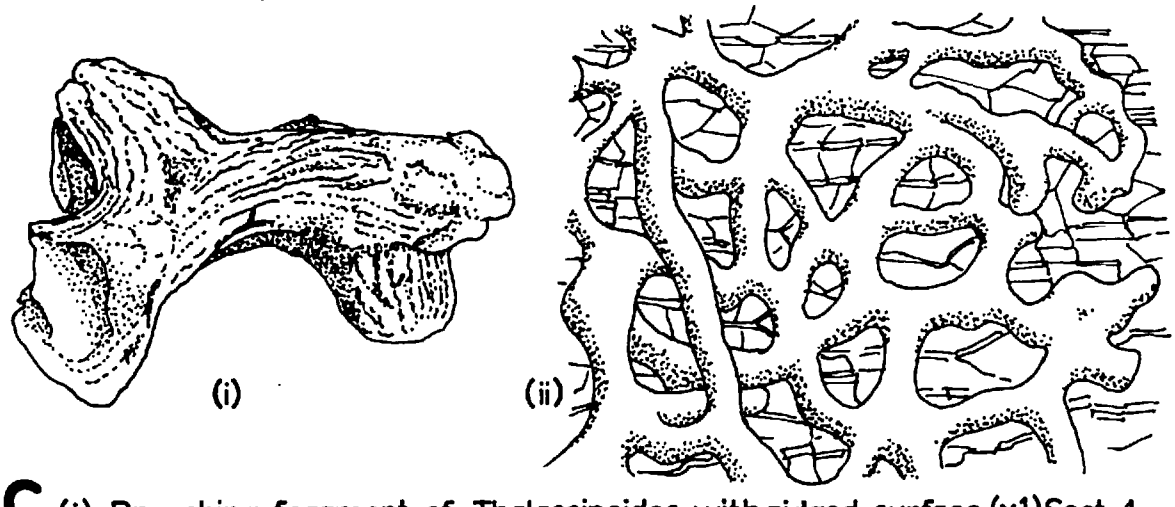
(ii) Similar specimen with one row of warts at the bases of the sides only. (x1) 400metres east of section 7.



(i) (ii)

b (i) Vertical section of a specimen intermediate between Ophiomorpha and Thalassinoides, with a warty wall in sand and no wall in shale interlaminae. (x1) Section 28

(ii) Vertical section of Thalassinoides burrowed shale showing its gradual upward replacement by sand. Unit 2m thick, section 29



(i) (ii)

c (i) Branching fragment of Thalassinoides with ridged surface.(x1) Sect. 4

(ii) Underview of top of shale unit with plexus of Thalassinoides (x0·5) Section 31

Figure 4.16

passing along their lengths into one another. At section 28 the vertical section through an Ophiomorpha - Thalassinoides burrow is characterised by a warty wall in the sandy interbeds but is unwalled where it passes through shale interbeds (figure 4. 16b(i)).

(iii) The largest types vary from 3·5 cm to 11 cms in diameter and have components transitional to the medium sized Thalassinoides in 23% of occurrences. The diameter is much more variable and the burrow system significantly less regular than before. They are common in lime - stones where they are visible excavating impure bands and the tops of interbedded shale units down to about 60 cms. The concentration of burrowing is rather similar to the small and medium sized forms but rather fewer components are present. Thalassinoides paradoxica (Woodward), noted by Kennedy (1967) from the chalk corresponds fairly well with this type.

Geographic distribution (figure 4. 15b): Small Thalassinoides root from calcareous sands and limestones, but they always occur in shales, silty shales or calcilutites. The presence of a coarse fill relates these burrows to the period of deposition of the unit above or to periods of non-deposition. Marine fossils are found in 50% of the units, and indicate shallow brackish and fully marine waters (the Crassostrea and Lopha biofacies)

Medium sized Thalassinoides are very common in fine grained sedi - ments throughout the area. They are found in 165 units, mainly inter - laminated sands and shales and limestones. As with the smaller types they often bioturbate the tops of shale units, rooting from coarser units and from sandy interlaminae in interlaminated sands and shales. Ophiomorpha and Caegichnus are the most commonly associated burrows and marine fossils belonging to the Crassostrea and mixed calcareous algae & Crassostrea biofacies. They indicate a wide range of shallow water marine and brackish water environments.

Large sized Thalassinoides occur in 40 units, nearly all limestones, and are closely associated with marine fossils, especially with the Crassostrea biofacies. Medium sized Thalassinoides and Caegichnus are the most closely associated burrows.

Ophiomorpha - Thalassinoides Discussion

The occurrence of examples passing along their length from medium sized Ophiomorpha into medium sized Thalassinoides indicates that these burrows were produced by the same organism. They were produced through different behaviour patterns.

Ophiomorpha is found in coarse-grained deposits and is characterised by a thick wall with warts. The latter structure is correlated with the necessity that animals living in unstable substrates have to support their burrows and prevent cavitation. The organism that formed Ophiomorpha burrows did so by packing the sediment probably by a mucus secretion, represented now by calcareous or silty material. Secretion probably took the form of repeated discharges of mucus around the burrow as excavation proceeded. The resultant irregular structure consists of a series of transverse rows of silt-cemented ball-shaped structures or warts. In most cases there is no difference between the size of the sand grains of the wall, and of the surrounding sediment. In a few cases, however, the grains in the former are smaller, and it is evident that the organism actually packed the sides of the burrow with mucus-cemented sand pellets.

Thalassinoides is typical of fine-grained deposits, though it commonly roots from, and is filled with sand or calcarenite. It is equivalent to the central tube of Ophiomorpha and is distinguished from the latter by the absence of a warty wall. The substrate was clearly stable and cohesive enough to support a burrow system without any supporting wall structure. That the shales were cohesive when the

burrowing took place is clear from the general lack of depression suffered by the horizontal components.

The modifications of Ophiomorpha characterised by the partial loss of the wall represent a series of forms intermediate between Ophiomorpha and Thalassinoides. They occur in sandy beds with thin silty-shale interlaminae indicating environments that are intermediate in stability between the sands and the shales.

Seilacher (1967) noted that burrows made by Callianassa on Recent beaches were without the usual lining of mud pellets when excav - ated in cohesive muds.

Ophiomorpha is generally characterised by straight unbranched vertical components up to a metre long with regularly branching horizontal systems at various levels. Thalassinoides burrows however, are gener - ally much less deep, the horizontal plexi rarely exceeding 30 cms depth. Probably the organism that created them found it necessary to burrow much deeper in the relatively unstable sands than in the cohesive fine grained deposits that were much less easily reworked. A feature of the burrows of the living decapod Callianassa is their variable geometry. In sandy beaches they tend to be vertical, but are horizontal and anastomosing in other environments (Seilacher 1967). The 3 size types recognised in each ichnogenus possibly correspond to each other - thus the small Thalassinoides probably represents the burrows of the small Ophiomorpha in shale. Within one ichnogenus, however, each size type is transitional and there are not sufficient grounds for considering them as separate ichnospecies.

Interpretation: Ophiomorpha burrows were recognised by Weimer and Hoyt (1964) as identical to those produced at the present day on the sandy beaches of South Carolina by the ghost shrimp Callianassa major Say. The presence of widespread chela of Callianassa spp. in

the Zelten area closely associated with the burrows supports its identi - fication as the burrower there. The chela are rarely found within the burrows, however, possibly due to the habit callianassids have of leaving their burrows when they are about to die (Schafer 1962).

In the past several authors have ascribed Thalassinoides type burrows to Callianassa sp. Glaessner (1947) for instance, examined unwalled branching burrows with swollen nodes from the Eocene Pebble Point beds of Victoria, and attributed them to C. bakeri, chela of which were abundant in the sediment. Ehrenberg (1938) and Bromley (1967) also regarded Thalassinoides as the work of Callianassa. Homogenisation of sediment as by the medium sized Thalassinoides (fig 4.16(i)) has been described by Warme (1967) from a Californian lagoon and attributed to species of Callianassa. The presence of elongate ridge or scratch marks on the walls of some of the specimens of Thalassinoides from the Zelten area indicates that they were created by crustaceans.

The difference in geometry of Ophiomorpha and Thalassinoides is partly a result of the feeding habit. Callianassids are "detritus sifters", that is they sift sediment for microscopic food particles. Those that live in sand strain the material that is constantly intro - duced into the top of the burrow, and so retain a fairly simple geometry. Burrowers in cohesive silts and clays, however often do not have this constant supply of sand and excavate as comprehensively as possible detritus-rich layers within the sediment. Extensive and repeated re - working results in the transformation of a clay into a series of sand filled passages.

There have been many accounts of the ecology of Callianassa, a world wide tropical and temperate genus, but other than Weimer and Hoyt (1964) none has mentioned the peculiar warty wall of the burrow. This is probably largely because they have the form of Thalassinoides, though non-impregnated burrows would probably not show up the wall

structure.

The burrows of C. major studied by Pohl (1946) on the sandy shore of Beaufort, North Carolina have the structure of Ophiomorpha, being composed of long vertical components up to 2 metres deep, with repeated horizontal branches and a dark, rust-coloured burrow lining 0·7 cm thick. These callianassids were restricted to firmly packed sand on open shores exposed to the sea between half and three quarters of the way up the beach. The examples of C. major described by Weimer and Hoyt (1964) from Sapelo Island, North Carolina reached a maximum con - centration on the lower foreshore of open beaches. They were noted however down to 5' below low water and were assumed to occur below that level. The warty wall was described in detail and the cementing agent identified as collophanite (amorphous calcium phosphate).

Burrows of Callianassa subterranea (Montagu) described by Shafer (1962) and Reineck, Gutmann and Hertweck (1967) from the North Sea resemble medium sized Thalassinoides. A network of unwalled horizontal tunnels with swollen chambers at the nodes occur in muddy sands deposited in depths of 25 to 60 metres. The unwalled burrows of C. californiensis described by MacGinitie (1934, 1935) from the muddy intertidal flats of an estuary in California are also of Thalassinoides type.

Though none of the described species seems to occur in depths greater than 65 metres (members of the family Callianassidae occur in depths of 100 m), within itsrange it is hard to subdivide bathymmetric - ally. Thalassinoides type burrows have been reported from a wide variety of depths in muddy and muddy sand substrates. Ophiomorpha type burrows on the other hand, have only been described from the clean sands of the intertidal and very shallowest subtidal zones, with a maximum concentration in the former. Thus from a palaeobathymmetric point of view, Ophiomorpha as a much better indicator than Thalassinoides. From their associations they both seem to prefer areas of slow or non-

deposition and both seem to be euryhaline. An algae cover to the sub - strate was probably present, providing abundant organic matter in the sediment.

It is clear that in the Zelten area Ophiomorpha and Thalassinoides burrows are at least in part equivalent. It is obvious, however, that not all of the Thalassinoides burrows that have been described have Ophiomorpha equivalents, as they are excavated by a large number of species. It seems generally true, though, that in both the fossil and in the Recent, that Thalassinoides occurs in fine grained sediments while Ophiomorpha is restricted to sands.

It is concluded that the Ophiomorpha burrows of the Zelten area indicate an intertidal environment (related to the distribution of sand - which also tends to remain near the intertidal zone), While Thalassinoides burrows indicate both intertidal and subtidal environments down to a depth of perhaps 60 metres.

Ophiomorpha group burrows fall into the Fodinichnia group of Seilacher (1964).

Aestites nom. nov. (figure 4. 17,18)

These consist of large cylindrical irregularly branching, dominantly horizontal and depressed thick walled burrows, with a small central tube (figure 4. 17a).

The wall is between 1·5 and 7·3 cms thick, usually 4 cms, and has a smooth outer surface. It is composed of quartz grains set in a compact matrix of 0·4 cms calcite crystals. The sediment is frequently a lustre mottled calcareous sandstone or sandy limestone cemented in a similar fashion to the burrow. It usually produces an open structure composed of calcite balls on weathering, however, which cling to the burrows and give a pseudo-warty appearance to the wall. In many cases it is extremely hard to distinguish it from Ophiomorpha.

The sorting in the wall is generally better than in the sediment and the central tube, the grains on average 0·02 cm diameter (range 0·015 to 0·04 cm).

The horizontal and slightly inclined components are very often depressed slightly as a result of compaction, producing oval burrows with oval central tubes.

Dimensions of depressed specimens

2·0 x 1·7 cm

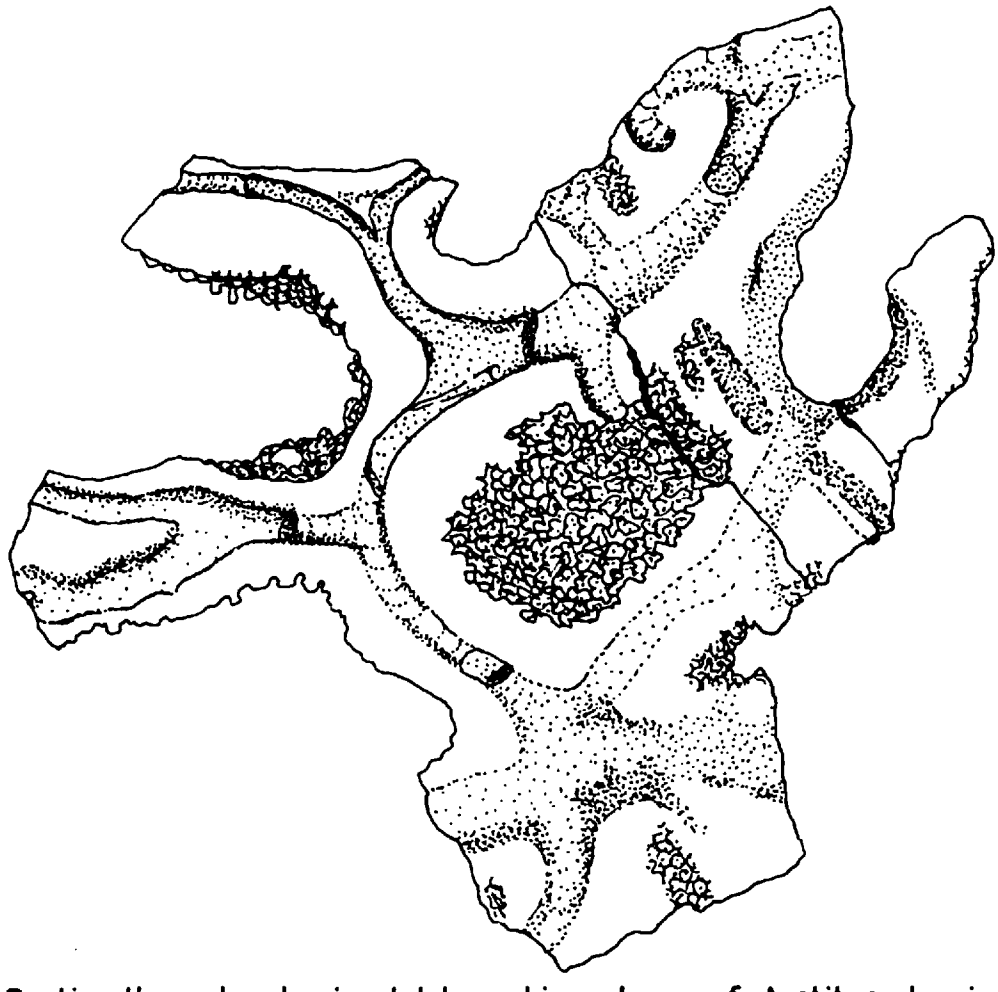
4.5 x 3.2 cm

8.0 x 4·0 cm

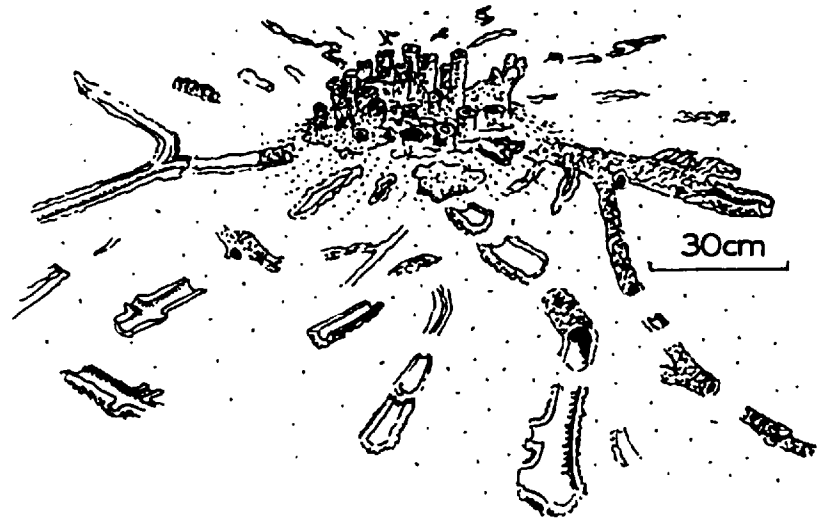
7·0 x 2·5 cm

2·5 x 0·8 cm

Sometimes the burrow appears depressed but the central tube is excentric and cylindrical. In these cases a horizontal meniscus fill concave towards the central tube demonstrates that the burrow at any one time was cylindrical.



a Section through a horizontal branching plexus of Aestites showing the thick wall and small central tube. Note the knobbly outer surface due to erosion of lustre mottled sandy limestone. (x0·5) Sect 33



b Horizontal surface of sandy limestone with an Aestites complex Section 33

Figure 4.17

The central tube varies from 0•4 to 1•8 cms diameter, but is typi - cally 0•75 cm. It is filled with the same material as the host rock - illsorted calcareous sands. Usually enlarged bulbous areas occur at the nodes of branching tubes.

Branching is dichotomous, the angle varying from 50 to 120°, and the length of internodes from 6•0 cms to over 1 metre. Smaller branches often follow the path of the parent, producing complex horizontal sheets. Sometimes burrows cut one another suggesting that cementation of the wall did not take place until after burrowing had ceased.

Closely associated with these dominantly horizontal massive bur - rows are smaller 0•9 to 1•5 cm diameter dominantly vertical cylindrical straight burrows with a thin wall and a relatively large central tube.

The wall is 0·2 to 0·5 cms thick and as before consists of lustre mottled sand. Owing to the less strongly developed cementation the burrows always appear warty and it is impossible to discern whether they originally had a smooth wall or not. They are indistinguishable from small and medium sized Ophiomorpha.

The central tube is the same diameter as in the larger forms (0•7 to 0•9 cms) and is often less calcareous than the wall. In a unit at section 20 the wall is cemented by ironstone and the hollow central tube has longitudinally striated walls. A silty area 0•12 cm thick surrounding it suggests that the wall has been packed.

Branching is frequent, every 10 - 12 cms, and nearly always at right angles, producing horizontal components. Two or more vertical tubes may be closely applied and even burrow through one another. The typical pattern of burrowing is well developed at section 33 in a calcareous sandstone 1 metre thick. On a horizontal surface 15m x 15m ($225m^2$) near the base, 9 well-spaced burrow systems occur. From a central high mound 0•5 cm diameter thick horizontal components radiate

straight outwards and downwards in all directions for more than 2 metres branching every 30 cms in a Y-fashion to produce a dendritic pattern (figure 4. 17b).

From the centres of these mounds crowds of vertical thin walled forms arise and pass up to the top of the unit giving off horizontal connections at various levels. There are often over 50 vertical tubes above a burrow system.

The pattern is often not so simple or complete: the two types may be mixed seemingly randomly or one may be absent - they occur together in only 40% of the units.

Geographical distribution (figure 4. 18a): These burrows are very characteristic of calcareous sandstones and sandy limestones associated with Caegichnus and other burrows. Its distribution dies out east west. They have clearly the same sort of burrow pattern as medium and large Ophiomorpha - a long vertical component passing downwards into a horizontal one, but are distinguished by the multiplicity of the vertical components and the peculiarly thick basal horizontal members. Possibly its distribution in more calcareous beds than the

Ophiomorpha burrows accounts for the thicker cemented wall, while a large number of vertical components may have been necessary if the existing burrows were continually becoming clogged with sediment. Most of the calcareous sands were probably laid down in high energy channel environments (see sediments) where there would always have been much unstable sand.

Globichnus nom. nov.

Derivation of name: Refers to the globular-shape of these burrows.

Description: Hemispherical, ovoid, mushroom or bell-shaped sand filled structures of various sizes occur in calcareous sands, sandy limestones and interlaminated beds (figure 4. 18b).

They are very variable in size, smaller ones measuring 5 or 10 cms long by 4 or 7 cms wide by 2 - 3 cms high. They have a generally smooth or slightly knobbly 0•1 cm thick calcareous or silty outer casing and occasionally internal concentric structure. The latter is brought out by rings of silty material 0•05 cm thick (figure 4. 19a (ii)).

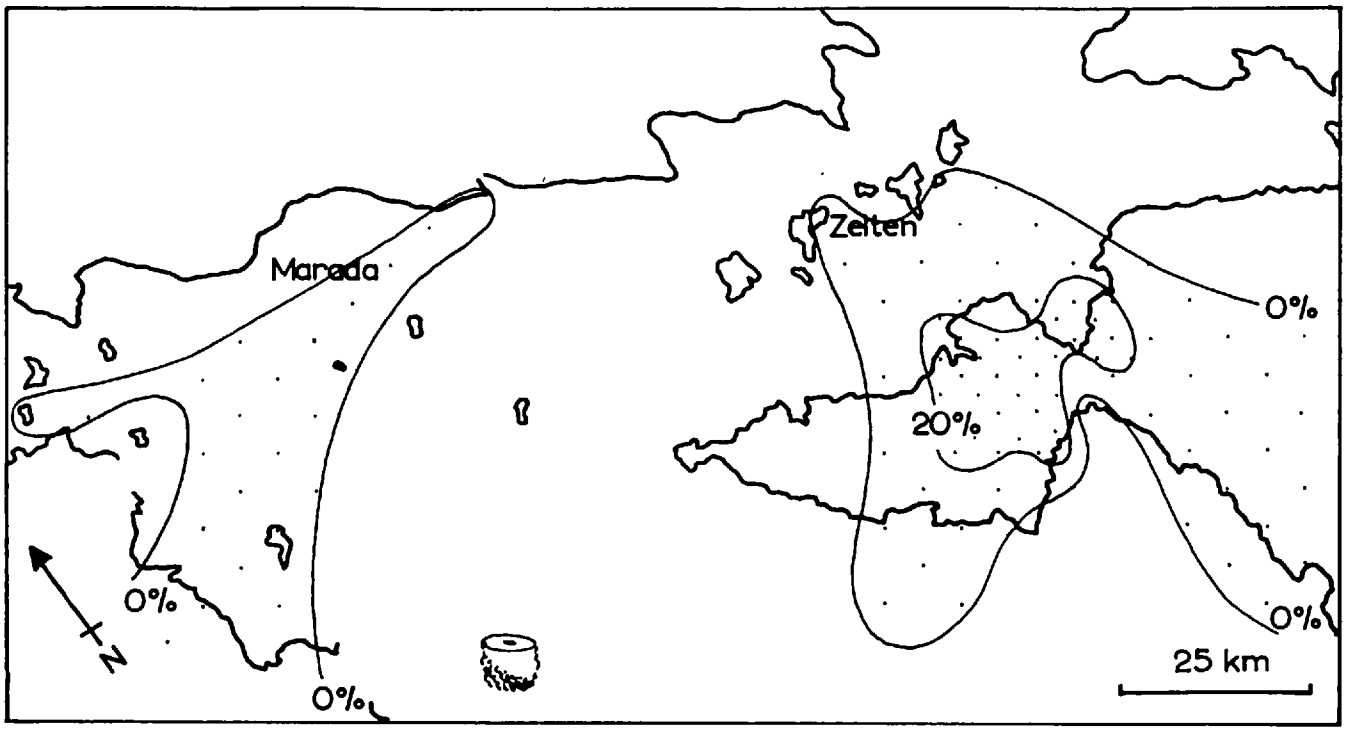
Larger specimens are generally oval-hemispherical and may measure 14 cms long by 11 cms wide by 9 cms high. They have an irregular outer surface without silty material and are generally filled with shelly or gritty material.

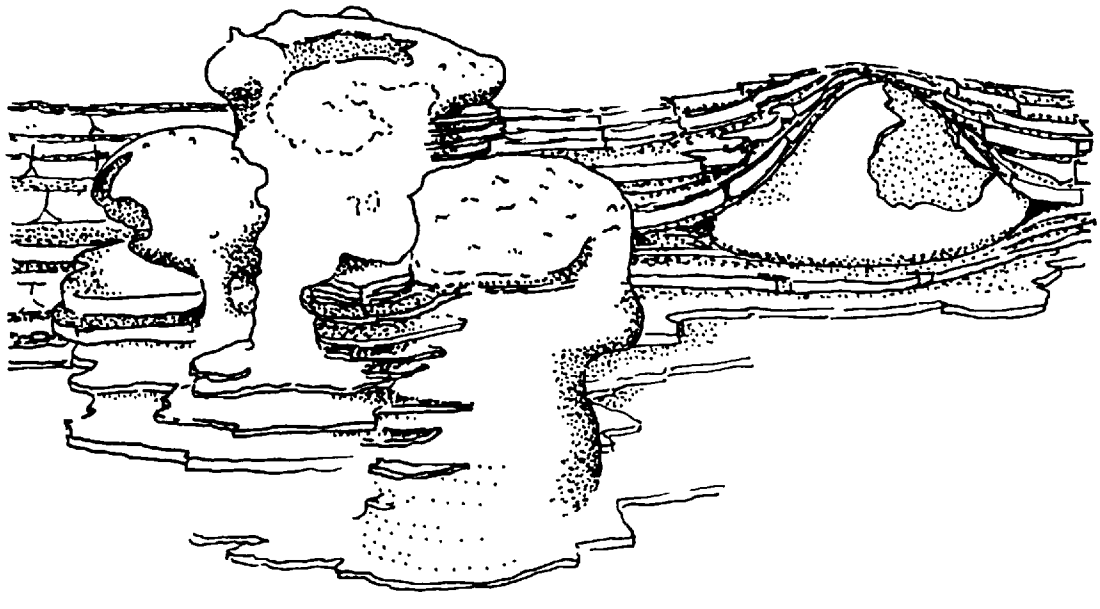
Both types are often riddled with branching worm burrows and may have Caegichnus or Alukichnus passing into them (figure 4. 19a(i)).

Geographic distribution: They are always associated with marine burrows, most commonly with Caegichnus, Ophiomorpha and Needleichnus.

Interpretation: They are not thought to be chambers belonging to Ophiomorpha or Caegichnus burrows, as neither of their correlatives in the recent has such structures. Their shape is similar however, to the cavities formed in recent tidal flats by Crabs (Evans 1966). Small or large rounded shelters with smooth internal walls are common in sands and sandy mud flats on the North Sea coast (personal observation) (photo 4. 5a). These burrows fall into the Domichnia group of Seilacher 1964.

a Percentage distribution in sections of Aestites





b Group of Globichnus. Vertical face of shale with thin sand interlaminae. Note the thin silty case and the sand fill. (x0·6) Section 34

Figure 4.18

Scutellichnus nom. nov. (figure 4. 19, 20)

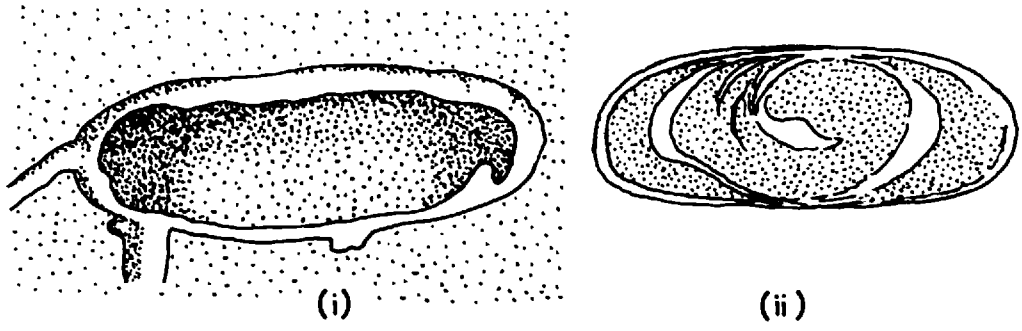
Derivation of name: Refers to the organism that was responsible for these burrows.

Description: Flattened meandering horizontal tracks cover large areas of a bedding plane at the top of a cross stratified calcarenite at section 23. They are 7·5 cm wide and over a metre long (photo 4. 1b). Their cross section is like that of a saucer, the sides having a relief between 1 and 1·5 cms (figure 4. 19c) and they are characterised by a well marked longitudinal trilobation (figure 4. 19b). The central portion 2·5 to 4·0 cms across is also saucer shaped and is often raised a few mms. Transverse grooves and ridges cut across this trilobation dividing it up into segments between 0·5 and 1·3 cms thick. The latter are curved and at the sides disposed at 60° to the length of the trail (figure 4. 19b).

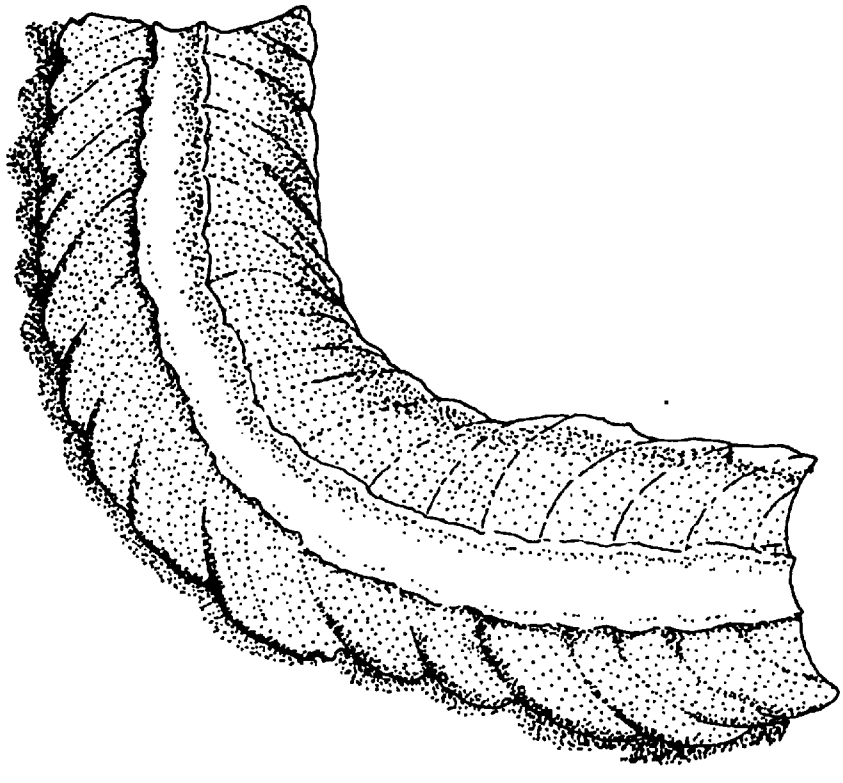
The trail path is generally sinuous but may have sharp geniculations and even double back upon itself (figure 4. 20b). It is formed of calcarenite without large shelly fragments and is slightly finer grained than the surrounding sediment.

Smaller examples of exactly the same pattern 3·5 to 4·5 cm in diameter occur in the same bed.

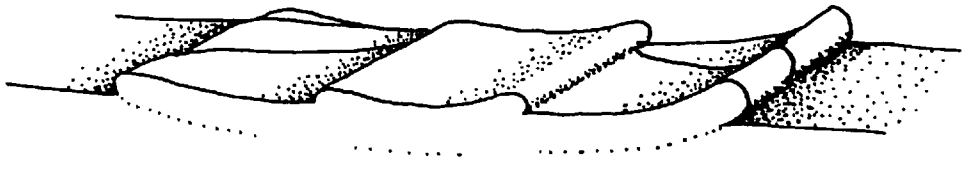
Interpretation: The trails are Repichnia which occur in a unit rich in scutellids. They very much resemble the trails left by recent species on the carbonate banks of Key Largo Coral Reef, Florida described by Kier & Grant (1967) (figure 4. 20a). Particularly similar are those of Encope michelini Agassiz and Leodia sexiesperforata (Leske) which burrow either on the surface or just below it. The animals move along with their anterior ends very slightly tilted downward so that their posterior ends protrude above the sediment. The longitudinal trilobation developed in the trails of these forms is caused in part by the



a (i) Globichnus re-excavated by Caegichnus. (x0·6) Section 39
(ii) Vertical section of specimen showing concentric structure (x1) Section 39



b Scutellichnus. Horizontal surface of calcarenite. (x0·5) Section 23



c Diagrammatic transverse section of Scutellichnus showing relief. (x1) Section 23

Figure 4.19

anterolateral notches and in part by the posterior lunule.. The forward inclination of the test accounts for the saucer-like cross section of the fossil trails, while the curved transverse grooves are probably due to a rhythmic forward jerking of the test as it moves along bringing the posterior end downwards. The grooves are thus probably concave in the directions of movement. The strong longitudinal trilobation indicates that the burrower had an angular outline and lunules.. Though no Scutellids occur associated with the trails, three species are present in the unit: Scutella brichettii, Scutella stefanini and Echinodiscus fuchsi. The last is the burrow-former, having the shape and both small and large examples fitting both sizes of trail. The depth of water indicated by the fossils is between 3 and 7 metres. Resting traces of the body and side- and tail-fins of Flatfish (Schafer 1962, p. 295) also resemble these structures, but it is not thought as likely that they were caused by these animals.



Photo. 4.5a Mud flat in intertidal zone in the Wash, with Crab burrows. Rular is 6" long. Photograph kindly loaned by Derek South.

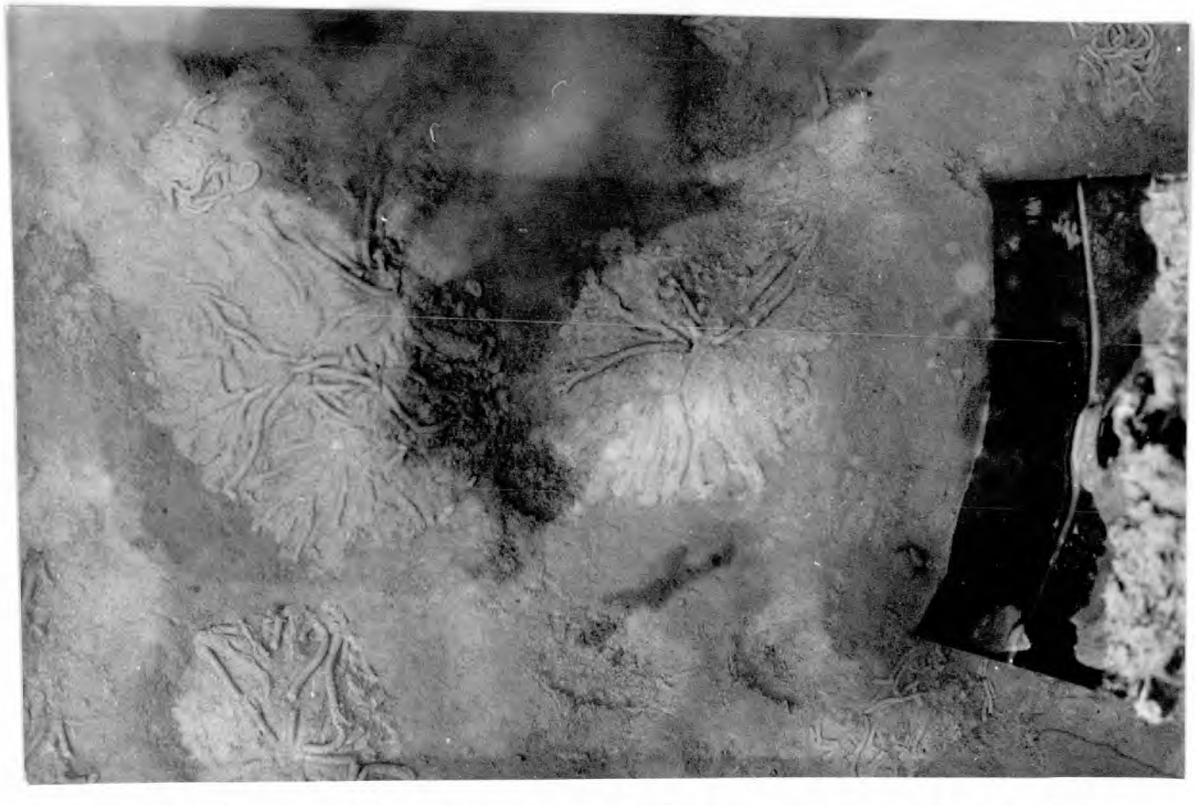


Photo. 4.5b. Faecal casts of Arenicola marina in a muddy sand flat. Photographed at low tide in 6" of water. Blakeney, Norfolk.

Faecal Mounds (figure 4. 20,21)

Very variable downward radiating mounds of rugose or smooth tubes are present in 4 units. In one case a series of 0·8 cm thick sand filled components radiate downwards 2·5 cms over a radius of 14 cms. The tubes are rugose and consist of sand with a thin irregular silty case, (figure 4. 20c).

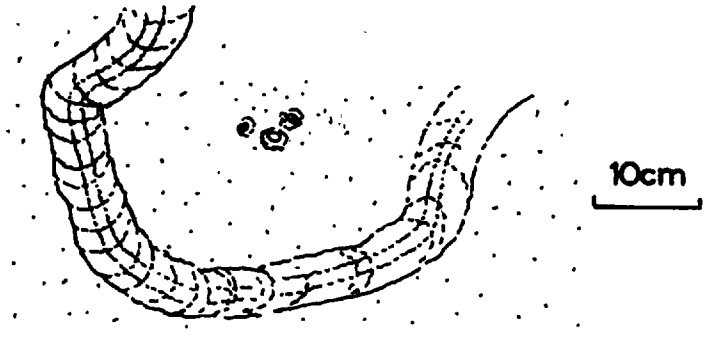
In a lustre mottled calcareous sandstone at section 38, two closely associated faecal mounds occur on one bedding plane, the whole structure measuring 25 cm x 9 cm by 6 cm high. At the base the components have fused to form a dense continuous mound of sand 7 cms across. Their diameter varies from 0·6 to 1·1 cm and they have the same structure as before (figure 4. 21a).

Geographic distribution: Faecal mounds occur in calcareous sand - stones and limestones in both the Raguba and the Jebel Zelten sections.

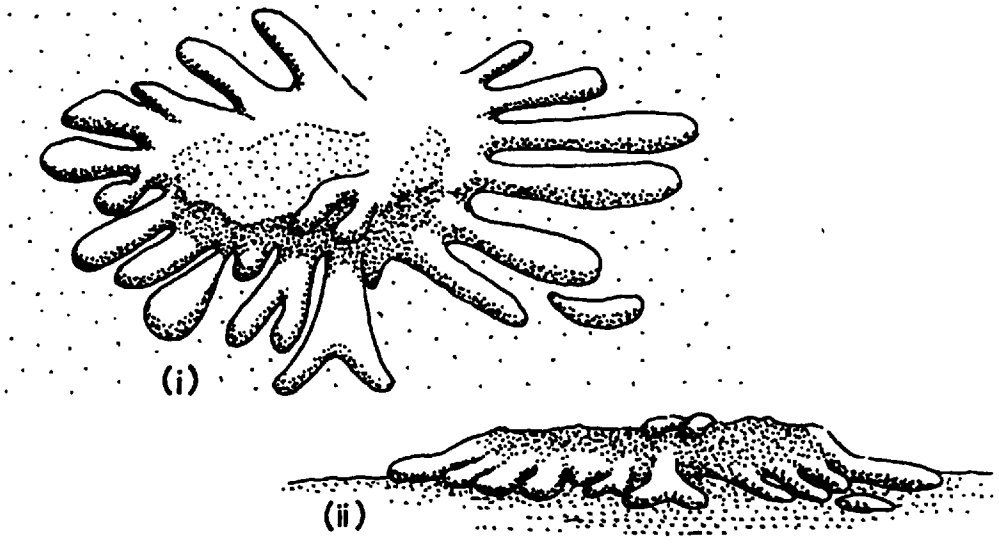
Interpretation: These structures closely resemble faecal mounds produced by Arenicola marina on the intertidal sand flats of the North Sea coast (photo 4. 5b). The latter, typically 18 cms across and up to 2 cms high have the same radiating pattern but the casts consist of smooth tubes. They only form in patches of sand flat that remain under a few centimetres of water at low tide. In dry areas the faecal casts are very highly coiled. Arenicola casts on open sandy flats are swept away by the incoming tide, but slightly muddy faecal mounds are not easily eroded and are often preserved. Quite high faecal mounds are built up by Arenicola in sheltered pans in the salt marsh .The structures are thus interpreted as faecal mounds, produced by worms or crustacea. The absence of any associated burrows suggests the former. Faecal mounds produced by worms and crustacea have been reported from muddy intertidal and the shallow subtidal deposits of many parts of the world.



a Trail of Encope michelini Agassiz. Ridges made by posterolateral notches and median row of sand grains by posterior lunule. (after Kier and Grant 1967)



b Horizontal surface of calcarenite with Scutellichnus trail. Section 23

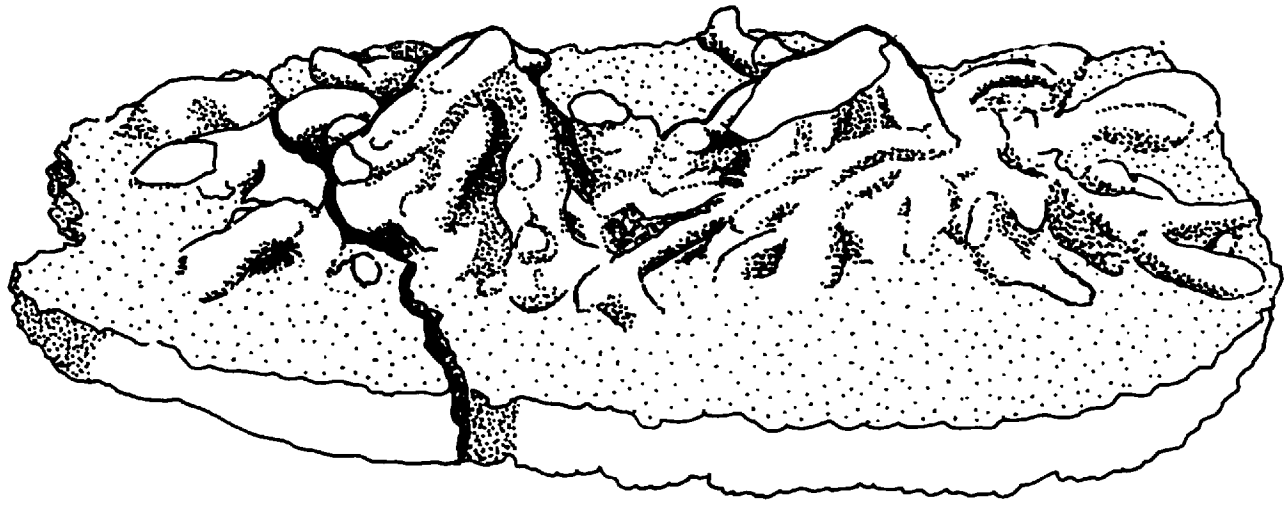


c (i) Faecal mound. Horizontal surface of calcarenite. (x0·5) Section 23

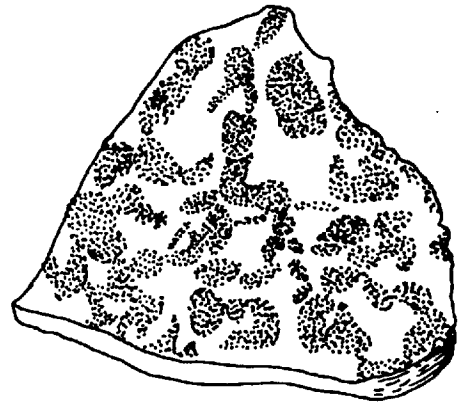
(ii) Side view of the same specimen to show relief.

Figure 4.20

Faecal mounds resemble many burrows that have been regarded as feeding burrows e.g. Asterosoma, Bifasciculus, Spongia ottoi.



a Closely associated pair of faecal mounds with rugose components. (x0·3) Section 38



b Horizontal surface of shale with tear shaped sand balls (x2) Section 4

Figure 4.21

Sand balls

Description: Irregular, but usually round patches of sand grains 0·8 cms long occur on thin laminae in one green shale unit in section 4. They are rather variable in shape, some being round or egg-shaped, others tear shaped. They are up to 0·2 cms thick, though they have clearly been compacted. On a bedding plane 480/10 cm^2 is a typical concentration (figure 4. 21,b).

Strings of unjoined or o. ed patches 3·0 cm long, or concen - trations producing large patches of silty sand occur on some bedding planes.

Interpretation: The dominantly egg-shaped structure and the ir - regularity of distribution suggest that they are sand balls produced by some endobiontic animal. The preservation in shale is significant. Sand balls are absent from sand units because they are largely destroyed by current activity, and the remainder are not sufficiently differentiated to be noticed.

CHAPTER 5

THE ICHNOFACIES

The burrows have been grouped, like the fossils, into recurrent assemblages, termed ichnofacies.

For each ichnofacies the percentage distribution in each of the rock types and the association with the biofacies have been noted.

The environment represented corresponds to the assumed ecology of the burrows typifying it. For obvious reasons this is not very specific, though as the burrows are all in situ the analysis unquestionably refers to the bed in which they occur.

Ichnofacies I

This is characterised by the Ophiomorpha - Thalassinoides group by themselves and may be divided into two.

A) The Ophiomorpha ichnofacies: This is an ichnofacies typical of interlaminated sands and shales, calcareous sands and limestones and occurs in 45 units. It is associated with 13 marine biofacies, most commonly the Crassostrea, smooth-bivalve/turreted-gastropod, spheri - cal calcareous algae and Capsa biofacies, indicating a wide salinity tolerance and moderate to high current activity. The depositional rate was generally slow and the substrate sandy and organic rich. The en - vironment was probably restricted to the lower part of the intertidal zone and the very shallow subtidal zone down to about 5 metres.

B) The Thalassinoides ichnofacies: This is found in 175 units, mainly limestones and interlaminated sands and shales. It is more closely associated with marine fossils than the Ophiomorpha ichnofacies, most commonly being found with the Crassostrea, Lopha, mixed calcareous algae and Crassostrea and the spherical calcareous algae biofacies.

ICHNOFACIES		n° of units	% occurrence in sediments								% association of burrows / biofacies					
			limestone		calcareous			sandy	unconsolid							
			lst	shale	snd	sh	inter	lstone	sand	shale	over 90	80-90	70-80	60-70	50-60	40-50
1a	Ophiomorpha	45	30		23	3	35	8								
1b	Thalassinoides	175	48	2	10	13	24	3								
2a	Ophiomorpha/ Caegichnus gp.	69	13		30	1	33	23								
2b	Thalassinoides/ Caegichnus gp.	28	33		15	4	37	11								
3	Diplocraterion	11	9			36	54									
4	Corophioides	5			20		40	40								
5	Argillites	9	33		22	11	33									
6	Caegichnus group	118	32	3	30	11	10	13	1							
7	Aestites	34	3		6			91								
8	Rootlet cast	22							77	23						

Occurrence and associations of the ichnofacies

Thalassinoides occurs in a number of environments indicating a wide range of salinity and depth, and variable current activity. They burrow in cohesive, fine-grained, organic-rich substrates in areas of slow or non-deposition. Both relatively low energy intertidal and higher energy subtidal conditions were represented.

Ichnofacies 2

This is characterised by Ophiomorpha and Thalassinoides occurring with the burrows of the Caegichnus group. As before it is divisible into two.

A) The Ophiomorpha-Caegichnus ichnofacies: This is characterised by Ophiomorpha with one or more of the Caegichnus group, especially Caegichnus and Needleichnus. It is most typical of interlaminated sands and shales and calcareous sands. As before it is associated with a number of marine biofacies, the most common being the Callianassa, Crassostrea, ribbed-bivalve and smooth-bivalve/turreted gastropod bio - facies. It indicates slow deposition on organic-rich substrates in areas of gentle to moderate current activity in the intertidal or shallow subtidal zones. It is closely associated with the Ophiomorpha ichnofacies but was probably typical of areas of slightly lower energy, perhaps partly protected by a barrier or algal zone from the open sea.

B) The Thalassinoides - Caegichnus ichnofacies: This is more closely associated with marine fossils and less common than the Ophiomorpha - Caegichnus ichnofacies, occurring in only 28 units. Biofacies occur in 53% of the units, the most common being those indicating fully marine conditions with influences of brackish water - the Lopha, Crassostrea, smooth-bivalve and turreted-gastropod and mixed calcareous algae and Crassostrea biofacies. In spite of the large number of units in which Thalassinoides is found by itself, this ichnofacies is rather uncommon. Burrows of the Caegichnus group are much more closely associated with

Ophiomorpha and this suggests that they were exclusively intertidal and shallow subtidal. The Thalassinoides - Caegichnus ichnofacies pro - bably indicates rather low evergy shallow protected environments where fine grained deposits accumulated.

3. The Diplocaterion ichnofacies

This is characterised by Diplocraterion in abundance, usually with Ophiomorpha. It nearly always occurs in interlaminated sands and shales or shales, and is taken to indicate intertidal or estuarine con - ditions. The rapidity of erosion and deposition indicated by the spreiten indicates high current activity, possibly associated with mi - grating channels.

4. The Corophioides Ichnofacies

This is characterised by the abundance of Corophioides and occurs in interlaminated beds and calcareous sandstones. It is taken to in - dicate an intertidal channel, creek, or sandy mud flat environment in salinities of perhaps 30°/oo. The current activity was generally moderate to high and the depositional rate slow.

5. The Argillites ichnofacies

Argillites and Ophiomorpha (44%) typify this ichnofacies, which occurs largely in interlaminated beds and limestones. It is taken to indicate mud flat conditions in the intertidal or shallow subtidal zone. The sediment was an organic rich interlaminated shale and sand or shale and the depositional rate periodic. Biofacies are fairly closely as - sociated, the most common one being the one characterised by Calianassa.

6.The Caegichnus group ichnofacies

This is characterised by one or more sand filled Caegichnus group burrows by themselves. The most common burrows are Caegichnus, Needleichnus, Capsites, Alukichnus and Premerites, and they occur in a variety of sediments, mainly limestones and clastic sands. They indicate an organic rich sandy substrate in which the deposition was either too rapid, or erosion was too frequent to allow permanent colonisation by Ophiomorpha/Thalassinoides. From a consideration of their recent correlatives it is probable they were partly intertidal, but the sands in which they occur may also have been partly subtidal; out of the depth range of Ophiomorpha and too coarse for Thalassinoides..

The salinity was probably variable; all the associated biofacies are in the euryhaline group - the Crassostrea, smooth bivalve - turreted gastropod, mixed oyster and bivalve-gastropod, ribbed bivalve and Capsa biofacies, and the rate of deposition moderate or rapid.

7.The Aestites ichnofacies

This is characterised by Aestites but contains a few other burrows, especially Caegichnus. It occurs almost exclusively in sandy limestones and calcareous sandstones many of which have basal clay pellet conglom - erates and are cross bedded or clearly have the geometry of channels. It is concluded that these burrows indicate high energy organic-rich rapid depositional sandy environments, probably in estuarine channels and in intertidal zones. The associated biofacies include the Crassostrea, continental, ribbed bivalve and Corbula basteroti biofacies all indic - ative of either euryhaline conditions or considerable mixing.

8.The Rootlet-cast ichnofacies

This contains one or more rootlet cast types and occurs in uncon - solidated sands and their associated shales, associated with the contin - ental biofacies. The burrows include Novisia, lignitic rootlets and

Dikaka, all interpreted as occuring in fluvial channel and levee sands and in swale fill and flood plain silts. Marine burrows, including Ophiomorpha, Alukichnus and Caegichnus occurring in one or two beds, represent short-lived transgressions of the sea up existing fluvial channels.

CHAPTER 6

THE SEDIMENTS

The sediments have been divided into a number of lithologic types for description, and each referred to a particular environment on the basis of its structures, geometry, fossils and burrows. The different environments do not correspond to the lithologic types, some of the former containing more than one rock type, some of the latter more than one environment.

For each type the composition, sedimentary structures, relationships to other lithologic types, fossils and burrows have been listed. The significance of these features in terms of the environment are then discussed.

Throughout, the environmental conclusions arrived at by Selley (1968) for each of the sediment types have been included. His systematic data should not be compared with this however, since the grouping of the sediments into lithologic types has not corresponded exactly. This is especially true of the shales.

The Limestones

(a) Calcarenites 186 units. (the offshore bar facies of Selley)

Description: Calcarenites are represented by highly fossiliferous horizontally bedded and cross stratified units (on average 1·7 metres thick). The carbonate content is always high, especially in coquinas, but in 35% of cases there is silty clastic material present, and to - wards the southern outcrop quartz grains are common.

The coquina limestones are often very porous, the shells or shell fragments being cemented by sparry calcite. A typical calcarenite at

section 9 contains a large number of shelly fragments (especially bryozoan) up to 2·0 cm in diameter, internal chambers of which are filled with drusy sparry calcite. The matrix consists of poorly sorted micrite with 2% subangular quartz grains. The rock is a bryozoan, mollusc, algal biomicrite of Folk's classification. (photo 61a)

Cross stratification occurs in 25% of the units: grouped large or small scale planar sets with 12° foresets are the more common (19%), grouped festoon or trough sets being restricted to 6% of the units. Massive rippled and laminated beds are rare (6%).

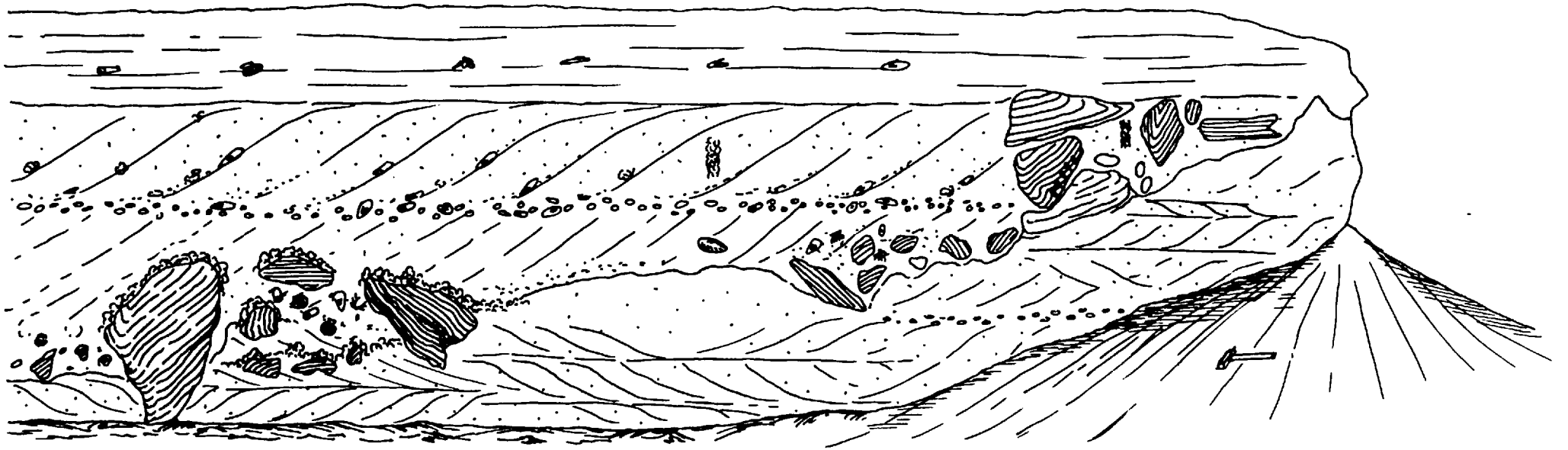
Conglomeratic lime mud pebble horizons occur within and at the bases of 21% of the units. The pebbles may reach boulder size (30 x 5 cms) and are frequently bored. At section 5 large bored and encrusted boulders occur in a channel cut in cross bedded calcarenite (figure 6. 1). At section 25 lime mud pellets contain empty radiating acicular structures after celestite or gypsum. Both are formed in this habit in early diagenesis at the present day in the intertidal and supratidal algal flats on the Trucial coast (D.J. Shearman, personal communication). Shell beds occur in 26% of the units, both at the tops or bases (16%) and within them (10%). Evidence of erosion or breaks in deposition between units may also be taken from burrowed horizons, truncated cross stratification and angular unconformities, and in total they indicate that in at least 16% of cases, the top surfaces are non sequences and in at least 26% of cases the basal surfaces are. In at least a quarter of their occurrences therefore, calcarenites follow or are followed by periods of erosion and non-deposition. Macrofossils occur in 89% (166) of the units, by far the most common biofacies being the Crassostrea, Trigonopora, Echinolampas, smooth bivalve, spherical calcareous algae and Lopha biofacies. These are representatives of stable bottom slow or non-depositional fully marine environments that are subject to influxes of brackish water. In most of the units (61%) fossils are

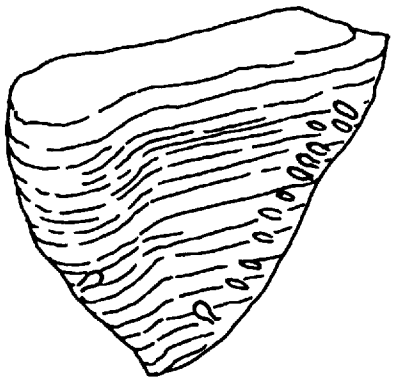
abundant, and though mainly fragmented, are in many cases well preserved. Units with complete or slightly broken specimens total 45%. This argues that in many cases there has not been much post mortem transport of skeletal material.

Bioturbation affects 36% of the units and consists largely of the Thalassinoides and Caegichnus group ichnofacies. In over half the cases the concentration of burrowing is low.

Geographic distribution: Calcarenites are abundant throughout the Zaggut and Zelten sections but are restricted to the tops of the Marada sections. They are present near the middle of the Raguba sections but are rare further south.

Environment: Generally high energy levels are indicated by the abundance of fragmentary allochems, the widespread cross stratification and the composition of the biofacies and ichnofacies. Periods of erosion are indicated by many of the non-sequential features (such as shell beds, burrowed or conglomeratic horizons and angular unconformities). In a few cases cross stratified channel fills occur, and in one case contain boulders of calcarenite derived from erosion of a calcarenite unit (figure 6. 1). Penecontemporaneous lithification of limestone to form "beach rock" occurs in intertidal zones of carbonate areas of deposition at the present day (Ginsburg 1957). All of the important biofacies indicate slow or non-depositional conditions on an algal or algal-free substrate in areas of gentle to moderate, but also high current activity. Normal marine salinities were evidently operational for much of the time but in the composition of the biofacies there is abundant evidence of periodic influxes of brackish water. Many of the calcarenites were deposited intertidally as barriers or offshore bars, but the micrite content, burrowing and fossils indicate that many were deposited in depths of down to 30 metres. Probably they often represent the deposits of channels.





Exposure illustrating rapid lithification of calcarenite. Boulders of limestone are encrusted with calcareous algae on their upper surfaces. The dip within the boulders has been indicated. Hammer is 23cm long. Section 5

(left) Boulder (near right of outcrop) with flasks of Gastrochaena squamulosa.

Figure 6.1

b) Mixed Calcarenites and Calcisiltites (154 units)

Description: These consist of richly fossiliferous illsorted horizontally bedded limestone units on average 1·6 metres thick. Very commonly the units are composed of interbeds of dominantly calcarenite and calcisiltite (40%), while massive or cross stratified units are rare. Commonly there is some clastic silty or gritty material present especially at the bases of units. At the tops of several of the sections the beds are mottled red and green due to the silty material present.

An example from section 17 contains micritic bryozoan fragments 1 cm long in an illsorted matrix of micritic shell fragments and micrite. Probably the micritic shells are due to algal infestation. As with the calcarenites, the rock is a bryozoan biomicrite of Folk's classification.

Conglomeratic beds composed of calcilutite pebbles or fragmented silty laminae occur at the bases, or at metre intervals throughout 28% of the units. About 10% of the pebbles are bored. The units are over - lain and underlain by breaks in deposition (represented by shell beds, conglomerates, burrowed horizons and angular unconformities) in 29% of cases. The bases of these units are most frequently burrowed indi - cating that there was a pause in deposition, while the tops are represented by shell beds and conglomerates indicating active erosion.

Biofacies occur in 80% of the units, and the most common are the spherical calcareous algae, Crassostrea, Lopha, Trigonopora and mixed calcareous algae and Crassostrea biofacies. These indicate much more continuously marine conditions than those in the calcarenites, probably characterised by slow deposition with gentle to moderate currents on a soft lime algal muddy or sandy substrate in depths of 5 - 40 metres. Evidence of periodic influence of brackish water is rather less marked. Fossils are abundant in over half of the units, most commonly being broken only. Burrowing is present in 56% of the units, and is mainly

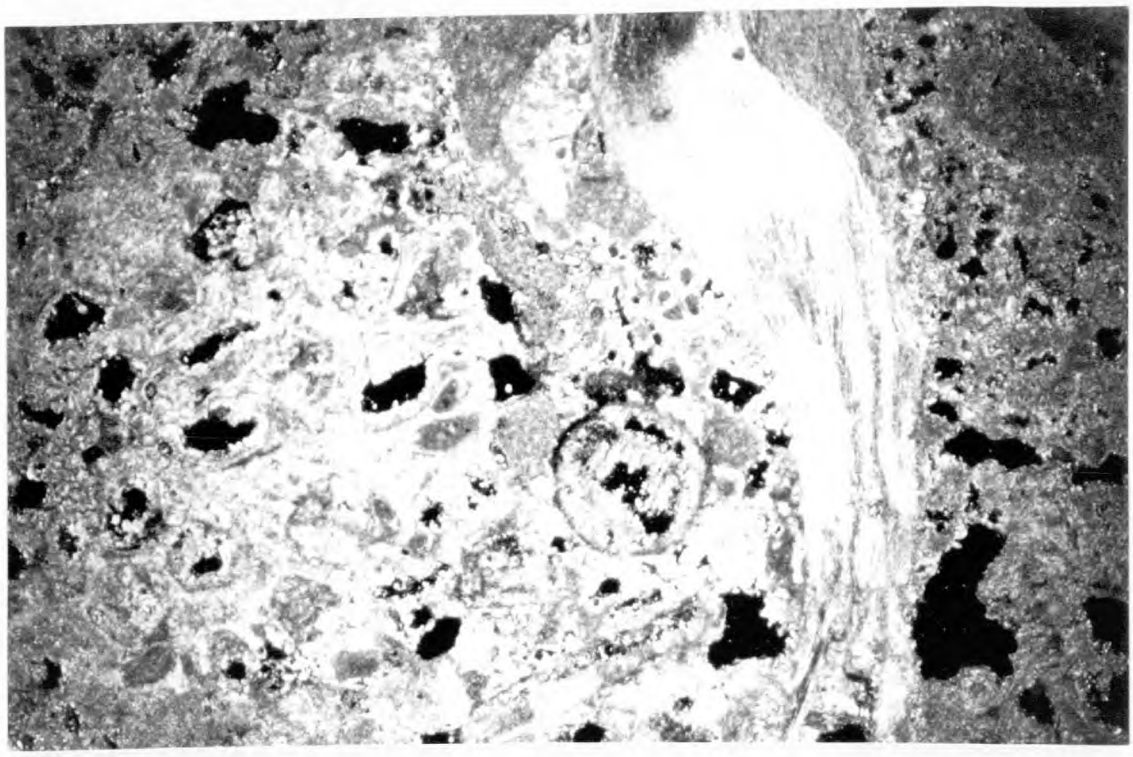


Photo. 6.1a. Thin section of a coarse calcarenite.
Section 9.

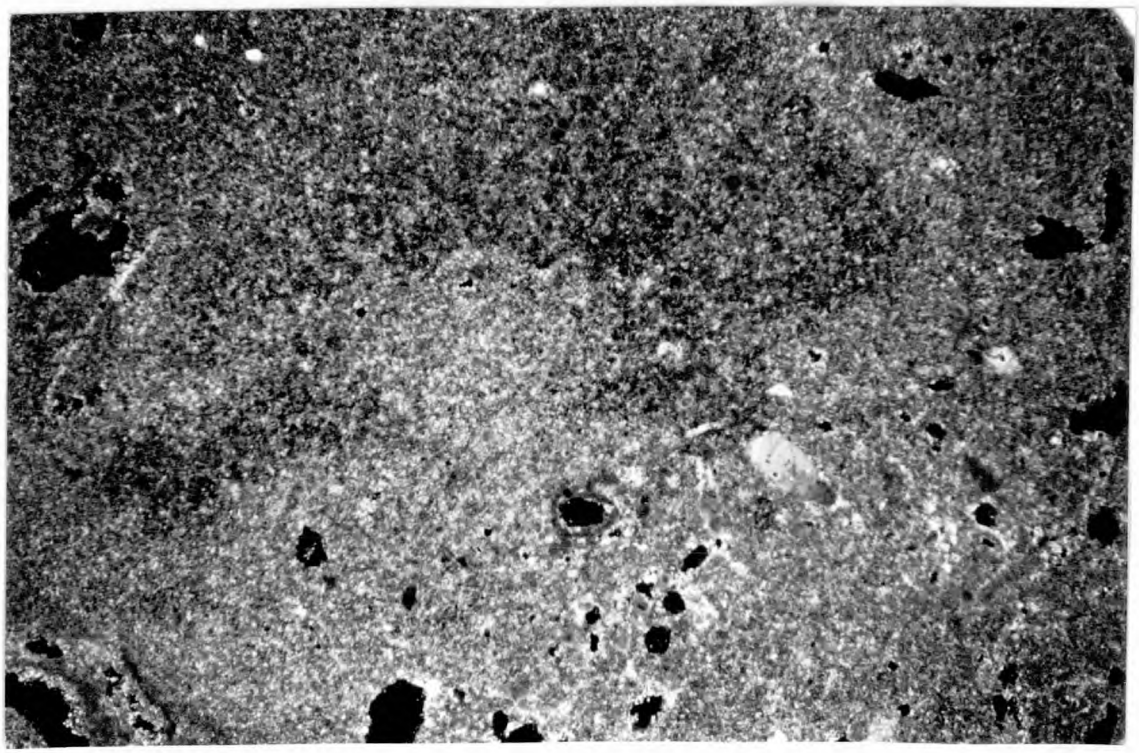


Photo. 6.1b. Thin section of a calcisiltite.
Section 4,

by the Thalassinoides and Caegichnus group ichnofacies. These are consistent with a range of nearshore and offshore environments. The concentration of burrowing is greater than in the calcarenites reflecting less physical reworking of the sediments.

Geographic distribution: These sediments are most abundant in the Zelten sections though they are very common throughout the Zaggut and at the tops of the Marada sections. They are more common in the centre of the sections in the north side of the Jebel Zelten than the calcarenites.

Environment: The abundance of interlaminated beds suggests that the environment was periodically affected by gentle to moderate currents depositing beds alternately richer and less rich in allochems. The biofacies, ichnofacies and texture indicate that the substrate was basically a slowly deposited soft to hard lime mud. Periodic influxes of brackish waters represented by the Crassostrea biofacies for example led to more rapidly deposited coarser broken shells, and repeated conglomeratic horizons.

Though most of the biofacies and ichnofacies indicate deposition in environments of 5 - 40 metres depth on algal substrates in areas subject to influxes of brackish water, a few probably indicate partly protected waters of shallow bays and lagoons:- These are characterised by the Caegichnus group, Ophiomorpha - Caegichnus and Diplocraterion ichnofacies and the smooth bivalve/turreted gastropod, mixed calcareous algae and bivalve-gastropod, Capsa and turreted gastropod biofacies.

c) Calcisiltites and Calcilutites (79 units)

Description: These consist of fine-grained horizontally bedded and interlaminated calcareous silts and calcisiltites, in beds on average just over a metre thick. In thin section the pure examples

appear as a well sorted micrite with about 1% well rounded quartz grains (photo6.Ib). Often there is a greenish or mottled colouration due to silty material. Conglomeratic horizons, like those of the mixed cal - carenites and calcisiltites occur either at the bases of units or through - out them at approximately metre intervals. The pellets are generally well rounded and less than 5 cms in diameter.

As before the evidence for breaks in deposition at the bases and tops of the beds occurs in about 30% of cases.

The fossils,which occur in 70% of the units are abundant and once again mostly broken or fragmented. The most common biofacies are the Trigonopora, Lopha, spherical calcareous algae and Crassostrea biofacies. These indicate similar environments to those of the mixed calcarenites and calcisiltites but with generally less brackish water influence. These therefore are the most marine limestones. Most of the bioturbation belongs to the Thalassinoides and Caegichnus ichnofacies. The concen - tration is usually low.

Geographic distribution: These sediments are uncommon in the Zaggut sections, being restricted to the tops. They are most common in the Zelten sections and also occur near the tops of the Marada sec - tions and the middle of the sections on the north side of the Jebel Zelten.

Environment: Deposition probably took place in calm waters of generally low energy in fully saline marine water in depths of 10 - 40 metres. The substrate was an algal rich soft cohesive lime mud, period - ically subject to slight erosion by currents. The sedimentation rate was slow, and the influxes of brackish water much less frequent than in the coarser limestones. The presence of significant quantities of silty material suggests proximity to a clastic source.

Summary of the Limestones

Selley (1967) showed that the cross stratification in the limestones had an east-west strike and bimodal dips that were predominantly dir - ected southward. There has clearly been some landward transport of material therefore.

The biofacies associated with the limestones have been tabulated to indicate their preferences for the grade of the sediment. The number of occurrences have been expressed as a percentage of the number of limestone units in each group

	Calcarenite	Mixed Calcarenite /Calcisiltite	Calcisiltite
Biofacies :- 1	10%	9%	15%
Biofacies :- 3	9%	15%	11%
Biofacies :- 2	2%		
Biofacies :- 4	3%	1%	1%
Biofacies :- 5	2%		
Biofacies :- 6	10%	3%	
Biofacies :- 7	16%	15%	11%
Biofacies :- 8	5%	5%	1%
Biofacies :- 9		1%	1%
Biofacies :- 10	5%	9%	4%
Biofacies :- 11	10%	2%	2%
Biofacies :- 12	1%	1%	
Biofacies :- 13	1%	1%	
Biofacies :- 14	2%	3%	2%
Biofacies :- 15	4%	1%	1%
Biofacies :- 16	1%	3%	2%
Biofacies :- 17	1%	2%	1%
Biofacies :- 19		3%	

Almost without exception the biofacies are less common in the

calcisiltites.

Selley's (1968 in press) interpretation of the limestones as re - presenting high energy offshore bars is unsatisfactory for the following reasons.

(a) They are not well sorted. Only 44·3% of them are clean calcarenites, 36·7% being mixed calcarenites and calcisiltites and 18·8% being calcisiltites. All of the limestones contain micrite, and were clearly not deposited in high energy conditions.

(b) Most of the biofacies indicate subtidal conditions, some in water depths of 40 metres. There is plenty of evidence that many of the fossils are near to, or in the position they occupied when they were alive. Many of them, for example the spherical calcareous algae, indicate muddy waters affected by gentle currents only in depths of 10 to 30 metres.

(c) Cross stratification is not as common as Selley supposed. His figure includes horizontal bedding, which he took to be a component of the complex cross bedding of the offshore bars. In fact, only 13·1% of the units have crossbedding with inclined foresets.

Shales associated with the limestones (128 units) (The lagoonal laminated shales of Selley).

Description: These consist of green organic-rich silty and gyp - siferous conchoidally fracturing calcareous shales that are interbedded with limestones. The units are on average 1·65 metres thick, but gen - erally occur in one of two ranges: 30 cm to 1·5 metres, and 2 metres to 8 metres. Sandy interlaminae are typical of thicker units but are usu - ally impersistent and unburrowed. Rarely, 30 cm thick burrowed cross - bedded calcareous sand interbeds occur. The sediments are always cal - careous and very often a distinct lamination is brought out by thin calcilutite horizons.

Gypsum sheets are very widespread on fracture planes disrupting laminae, and thick ribs up to 10 cms across follow larger bedding surfaces and vertical shrinkage cracks, especially towards the tops of units. In all occurrences the crystals are clearly secondary and probably represent an upward efflorescence.

The limestones are occasionally seen pinching out abruptly in shale units (figure 6. 2a). This indicates that considerable energy was involved in the deposition of one or other sediment types. In these cases which the shales are underlain by a break in deposition (31%) shell beds and conglomerates indicating high current activity and active erosion are common. At the tops of the beds the most common depositional break feature is a burrowed horizon.

Fossils occur in 31% of the units, the most common biofacies being the Trigonopora, Crassostrea, spherical calcareous algae and Idmonea biofacies, indicating normal salinity in offshore areas affected by periodic influxes of brackish waters. Most of the specimens are fragmented and are rarely abundant. Burrows occur usually in low concentrations in 7% of the units, the most common ichnofacies being Thalassinoides.

Geographic distribution: Shales associated with limestones have a restricted distribution within the carbonate regime. They are most common towards the bottoms of the Zelten and eastern Zaggut sections, though some occur at the tops. Thin rare shale units are found in the Marada and northern Jebel Zelten sections.

Environment: The biofacies of these shales are similar to those of the limestones with which they are interbedded, the general range of depth of deposition being the same (between 0 and 40 metres). They reflect periodic influxes of clastic material into the general area of carbonate deposition, and correlate with the intermittent influxes

of brackish water indicated throughout the limestones. The shales may thus be related to a brackish water source, or estuary, and represent its seaward expression. The thicker units, containing some sandy interbeds probably indicate relative proximity to the source, while the thinner beds represent relative distance. The individual units are rarely thick enough to be considered deltaic - most are no more than the fine grained sediments of an estuary deposited at and below inter - tidal zone.

The cohesive clays that were deposited provided an excellent or - ganic-rich substrate for Thalassinoides burrows and for epibionts, some indicating brackish conditions (especially Crassostrea gryphoides) but most indicating normal salinity in areas of gentle to moderate currents.

There seems little reason to suppose that all of these shales were deposited in a lagoon, as Selley suggested (1968 in press).

Calcareous Clastic Deposits (The Intertidal facies of Selley)

A) Calcareous sands (68 units)

Description: These comprise variable highly bioturbated yellow sands and calcareous sands interbedded with interlaminated sands and shales and shales with an average unit thickness of 1·65m. They are fine grained and usually well sorted, though gritty beds occur (13%). About half of the beds are calcareous and contain silty interlaminae and matrix. Lignite is present in 10% of the beds. Crossbedding is very common (40%) and is more commonly planar (66%), than festoon.

Clay pellet conglomerates occur in 29% of the units, some con - sisting of large flat pebbles and cobbles of silt up to 30 cms long representing slightly eroded silt and clay beds. They are nearly always associated with shell beds and are occasionally bored.

Fossils occur in 26% of the units, the most common biofacies being the Crassostrea, ribbed bivalve and Capsa biofacies. These indicate variable salinities in slow or non depositional areas. The Capsa biofacies occur as moulds in the clay pellet conglomerates. Most specimens are unfragmented and common, though poorly preserved.

Burrowing is extremely common and largley represented by the Ophiomorpha, Ophiomorpha - Caegichnus and Caegichnus group ichnofacies - the shallow water and intertidal indicators.

Geographic distribution: Calcareous sands occur most frequently in the lower halves of the sections on the south side of the Jebel Zelten and in the middle parts of the Marada sections. They are also present near the bottoms of the Raguba, northern Jebel Zelten, and Zelten sections.

Environment: Deposition took place in areas of moderate to strong current activity where there was variable slow to moderate deposition and erosion. The substrate was an organic rich sand and the fossils and burrows indicate depths of 0 to 5 or possibly 10 metres. The salinity varied from normal down to about 25 or 30°/oo.

Many of these sands represent intertidal sand flats or channel deposits and probably developed on exposed open coasts.

B) Silts and Shales (46 units)

Description: Green calcareous silty shale units interbedded with sands and interlaminated sands and shales have an average thickness of 2 metres, though there is a considerable range. Like those interbedded with the limestones, they are often gypsiferous (26%) and laminated. Nearly half have burrowed calcilutite interbeds and many are lignitic and ferruginous.

Bored clay pellet conglomerates are rather rare and occur at the bases of the 9% of the units.

Fossils occur in only 15% of the units, the mixed calcareous algae and Crassostrea biofacies occurring twice and others (numbers 11,12,16, 17,18) occurring once. They indicate environments similar to those of the sands. Burrowing is more common, affecting 39% of the units. It is mainly by the Thalassinoides and Caegichnus group ichnofacies and indicates shallow water soft substrates.

Geographic distribution: Shales associated with other calcareous clastic deposits occur in the lower part of the sections in the Jebel Zelten, especially on the north side. They are also common in the Marada sections, but are rare in the Raguba, Zelten and Zaggut sections.

Environment: Slow or non-deposition in fluctuating, generally gentle to moderate currents on an algal rich cohesive clay substrate is indicated. The range of depth was between 0 and 15 or 20 metres and the salinity varied from about 30 - 36°/oo.

Those units that are closely interbedded with the sands and interlaminated sands and shales were probably deposited intertidally: they contain Thalassinoides and Caegichnus group burrows and are generally less than 1 5 cm thick. Much thicker less burrowed shales occurring for instance in sections 24 and 25 were probably deposited subtidally and are transitional to the shales interbedded with the limestones.

C) Interlaminated Beds (107 units)

Description: Interlaminated rippled yellow sands and green silts and shales are closely associated with the calcareous sands and shales. Units range in thickness from 30 cm to 10 metres, with an average of 2.5m.

There is considerable variation in the percentage of sand against silt and clay; units consisting largely of sand with a few silty inter - laminae as well as those consisting largely of clay being included. As before, the beds are nearly always slightly calcareous. Rippling and crossbedding in the sandy interlaminae and a 1·0 - 3·0 cm lamination

in the silts and shales are common. Conglomeratic horizons consisting of bored clay pebbles and cobbles occur in 13% of the units.

Fossils occur in 28% of the units, usually in significant numbers, but generally broken or fragmentary. The most common biofacies are the Crassostrea, Callianassa and mixed Crassostrea and bivalve-gastropod biofacies. Burrowing is once again very important, occurring usually in high concentrations, in 71% of the units. The Thallassinoides, Ophiomorpha-Caegichnus, Ophiomorpha and Caegichnus ichnofacies are the most important. Burrows are most abundant in the calcareous bands, indicating rather slower deposition.

Geographic distribution: Interlaminated calcareous sands and shales are abundant in the lower parts of the sections throughout the area. They are especially common in the Marada, Raguba and Jebel Zelten sections, but also comprise many of the clastic deposits in the Zelten and Zaggut sections.

Environment: The sediments indicate deposition by wave action of alternating sandy and silty laminae in an environment with gentle to moderate current activity. Interlaminated sands and clays are very typical of intertidal flats (Van Straaten 1954) and estuarine channel flats (Oomkens and Terwindt 1960) where there are alternating tidal currents. Seasonal lamination may be produced in the subtidal areas of deltas but in this case the sands are not rippled. The geometry and association of the Zelten sediments suggests that they are intertidal, lagoonal or just subtidal.

The fossils and burrows indicate slow or non-deposition on algal rich substrates in depths of 0 - 5 or 10 metres in areas where the salinity fluctuates down to 30°/oo

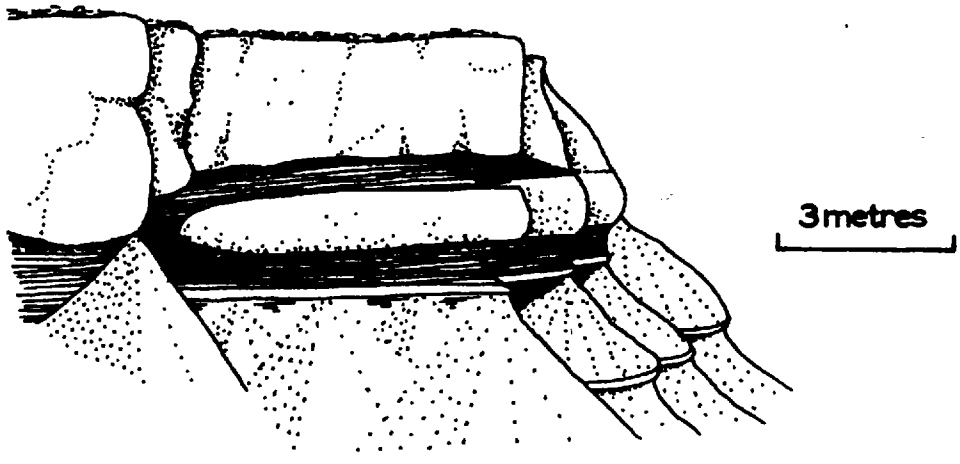
D) Channel deposits (12 units)

Description: In a few cases strongly discordant channels filled with upward-fi ning sediments cut through (A), (B), and (C). The best example, at section 39 is 35 metres thick and is closely as - sociated with a second channel. The basal 2 metres, consisting of a burrowed festoon bedded sandy limestone with large numbers of clay pellets, is followed by a thick succession of finely interlaminated pebbly, calcareous sands and silts dipping 12° to the southwest. It is extremely highly bioturbated throughout by the Corophioides ichnofacies. At the top of the channel there is 1 - 5 metres of inburrowed green silts with few sandy interlaminae (figure 6. 2b).

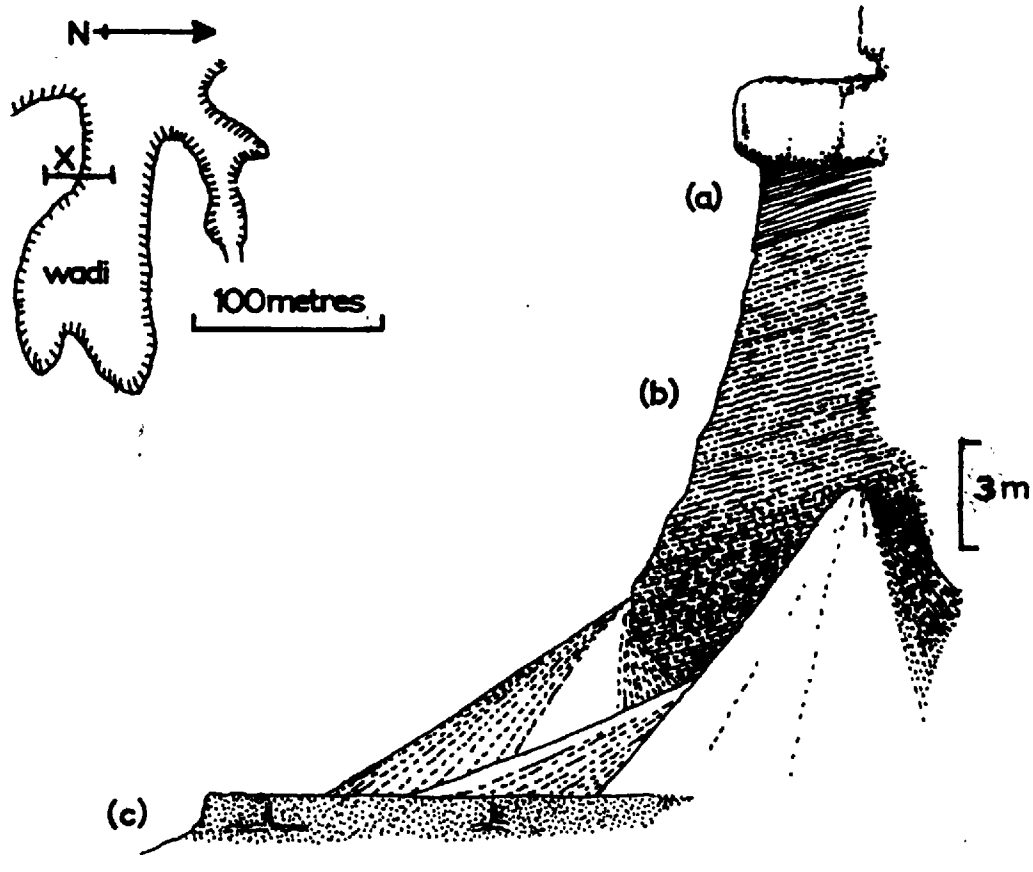
Fossils mainly occur in the sandy limestones at the bases of the channels and are represented by worn clay pellet moulds. The Crassostrea, smooth bivalve-turreted gastropod and continental biofacies are present, indicating a mixed source. Burrowing is largely by Corophioides and Caegichnus ichnofacies but the sandy limestones may be affected by the Aestites ichnofacies.

Geographic distribution: Five tidal channels have been recognised, most of them in the lower parts of the sections on the south side of the Jebel Zelten.

Environment: As indicated by Selley (1968) these channel deposits are similar to those of Recent tidal channels in the Dutch Wadden See (Van Straaten 1954). The festooned conglomeratic sandy limestone re - presents the basal lag,deposited by moving sand ripples along the channel floor. The highly Corophioides-bioturbated, 12° - dipping interlaminated sands and silts represent the sideways channel fill, or point bar, and are identical to channel fills on the tidal flats of the Lincolnshire coast (Evans 1965). The unburrowed silty material at the top represents the final rapid channel fill.



a Vertical face to show sharp-junction pinching-out of a calcarenite against an associated shale unit. Section 11



b Vertical section of tidal channel deposits at section 39
(a) Green silts with thin sandy interlaminae
(b) Finely interlaminated calcareous sands and silts highly bioturbated by Corophioides and dipping at 12°.
(c) Sandy limestone lag deposit.
The map of the exposure (top left) shows the position of the section, (X).

Figure 6.2

It is concluded that these deposits represent tidal channel-fills, and probably indicate conditions rather similar to those on the North Sea coast at the present day. Their average thickness (10m), however is much greater than the intertidal creeks which are rarely more than 2 5 metres thick, and much more closely resembles that of tidal channels, such as occur at Blakeney Point, Norfolk. Festoon bedded basal lags are typical of tidal channels also, but are not present in intertidal creeks.

Summary: Many of these calcareous clastic deposits show indications of having been deposited intertidally. The following criteria are thought to be strong indications of intertidal deposition:

a) interbedding of sand and shale units (thickness 1·65 m) covering wide areas.

b) interlaminated rippled sands and shales.

c) high concentration of burrowing by Ophiomorpha, Ophiomorpha - Caegichnus, Diplocraterion, Caegichnus and Corophioides ichnofacies (especially Ophiomorpha, Corophioides).

d) sands and shales passing upwards with apparent conformity into beds interpreted as fluviatile.

e) presence of tidal channels

f) presence of bored-clay-pellet conglomerates with eroded mud - flat faunas.

The calcareous clastic deposits in the sections have been examined in an attempt to recognise repeated vertical successions such as occur in present day intertidal flats.

The successions that build up over erosion planes consist largely of alternations of calcareous and interlaminated sands and shales. Shales are rare, reflecting the high current activity. Successions built up with seeming conformity over fluviatile beds normally coarsen upwards from an interlaminated bed and contain beds of shale.

sand (fluviatile)

(calcareous sand)

(shale)

(interlaminated sand and shale)

repeat

calcareous sand

shale

interlaminted sand and shale

sand (fluviatile)

Within the sediments interpreted as being fluviatile there are numerous thin burrowed calcareous sand units representing periodic marine transgressions up existing fluvial channels. The recognition of inter - tidal sediments in the Zelten area indicates that the Mediterranean sea was tidal during the period of deposition. The sea must have had a much less restricted contact with the open ocean to have a significant tidal range. This suggestion accords well with the relationships of the fossils. It was noted in Chapter 2 that a large number of the species and families present in the Libyan Miocene had tropical Atlantic relations in the Recent (while few had living relations in the Pacific and Indian oceans). There cannot have been much restriction westwards between the Mediterranean and Atlantic, a condition allowing a signifi - cant tidal range.

Mixed Clastics and Carbonates

A) Calcareous sandstones (95 units) (the offshore bar facies of Selley (part))

Description: Brown calcareous sandstones and sandy limestones resembling the calcareous sands occur in many of the more southerly sections, interbedded with calcareous clastics, other mixed clastics and carbonates, and sands and shales. They have an average unit

thickness of 2·15 metres, but vary from 30 cms to 8 metres thick. They usually have a lustre-mottled texture composed of well rounded coarse to very coarse sand grains within large calcite crystals. Upon weathering this gives the appearance of a fish roe in the more well sorted units.

Cross stratification is very common, occurring in 52% of the units. It is about two thirds planar and one third trough. Clay pellet conglomerates associated with gritty and shelly beds are common (35%), especially at the bases of units. They are frequently large flat bored fragments of calcareous silt.

Fossils, typically preserved as broken and worn moulds in the clay pellet conglomerates occur in 34% of the units. The smooth-bivalve-turreted gastropod, Corbula basteroti, continental and ribbed bivalve biofacies are most common, and indicate slow to moderate deposition in very variable salinities.

Burrows occur in 76% of the units, though the concentration is never great, the most common belonging to the Caegichnus group, Aestites, Thalassinoides, and Ophiomorpha-Caegichnus ichnofacies. They indicate very shallow water and variable salinities.

Geographic distribution: Calcareous sandstones are mainly concentrated in the lower and middle parts of the Jebel Zelten and Marada sections. A few occur in the Raguba and Zelten sections, but they are absent from the Zaggut sections.

Environment: The sedimentary structures suggest that these sediments are closely allied to the calcareous sands and are their more calcareous equivalents. The fossils and burrows confirm the shallow water intertidal environment, but generally indicate more mixing and much greater fluctuations in salinity. Many sandy limestones, interbedded with sands, represent short transgressions up existing fluvial channels. Towards the top of the sections on the south side of the

Jebel Zelten they form a continuous succession overlying calcareous sands. They represent intertidal beds enriched in carbonate due to very lengthy reworking prior to final deposition, and are probably in part related to an estuarine environment.

B) Calcareous silts and interlaminated shales and sandstones (30 units) (The estuarine channel facies of Selley (part)).

Description: Interbedded with the calcareous sandstones are gypsiferous calcareous silts and interlaminated beds on average 1·5 metres thick. Dominantly calcareous silt beds occur in 50% of the cases, interlaminated shales and sandstones totalling 42%. Bored-cobble conglomerates occur at the bases of 23% of the units, especially where they overlie fluviatile or clastic deposits. The carbonate material is often concentrated in burrowed bands throughout the units.

Fossils, represented by redeposited lime-mud internal moulds occur in many of the conglomerates. The Trigonopora, Crassostrea, turreted gastropod, ribbed bivalve and Corbula basteroti biofacies occur, indicating mixing and lowered salinity. Bioturbation, chiefly by the Thalassinoides and Caegichnus group ichnofacies, occurs in 43% of the units.

Geographic distribution: These sediments occur almost exclusively in the middle parts of the sections on the south side of the Jebel Zelten, though there are scattered occurrences on the north side and at Garet - el - Gehennch.

Environment: These beds are the equivalent of the shales and interlaminted sands and shales interbedded with the calcareous sandstones. They are more calcareous but contain the same biofacies and ichnofacies and indicate the same environment:- intertidal or just subtidal mud and interlaminated flats deposited by gentle to moderate currents in salinities varying down to about 26°/oo.

C) Calcareous sandstone channel deposits (85 units) (Estuarine channel facies of Selley (part)).

Description: Calcareous sandstone and interlaminated beds comprising calcareous sandstones and shales but laterally impersistent or having the geometry of channel deposits occur throughout the area. Sandy units, which are usually rather thicker (up to 15 m. thick) are more common (54%). Sandy interlaminated units are frequently conglom - eratic, containing bivalve-bored clay pebbles and cobbles. Planar and trough cross stratification occurs in 26% of the sandier units.

Fossils are abundant, occurring in 44% of the units. The most common belong to the Crassostrea, smooth bivalve-turreted gastropod, Corbula basteroti, Trignnopora and smooth bivalve biofacies, indicating very variable salinities in areas of moderate to strong current activity. Burrowing, occurring in 46% of the units is mainly by the Thalassinoides, Ophiomorpha-Caegichnus, and Caegichnus group ichnofacies.

There are three types of channel deposits.

(i) Small, strongly discordant channels up to 5 metres thick cut into intertidal/fluviatile sediments in the lower parts of the sec - tions at Marada and on the south side of the Jebel Zelten. They consist of highly burrowed shelly calcareous sandstones overlain by green shales and are rarely more than 100 metres wide. The cross stratified channel fill sediments are crowded with bivalves and vertebrate remains and within the channels frequent burrowed horizons, conglomerates and shell beds indicate repeated deposition and erosion.

(ii) A very much larger channel deposit occurs at the top of the sections. On the south side of the Jebel Zelten it is approximately 20 metres thick and stretches from section 30 to Garet - el - Beda, a jebel 30 kms southeast of section 39. It is almost completely unfossil - iferous (the Trigonopora biofacies occurring once) but is bioturbated,

especially at the base, by the Caegichnus group ichnofacies. On the borders of the channel crossbedded or massive calcareous sandstones are succeeded by interlaminated or interbedded calcareous sands and shales. Structures in these beds are impossible to see often, because of a high concentration of secondary gypsum disrupting the bedding. Towards the centre of the channel (at section 35 for instance) cross - bedded calcareous sandstones predominate throughout the thickness, though silty shale beds do occur. At the tops of the sections on the north side of the Jebel Zelten, the channel is rather similar in geometry and thickness but the beds are more calcareous and contain more silty shale interbeds.

The sections at Raguba pass upwards into a very thick crossbedded calcareous sandstone with channel geometry. It is at least 35 kms wide and at section 20 it is over 150 metres thick. At sections 20, 21 and 23 it overlies fluviatile sands, intertidal beds and shallow water lime - stones respectively. It thus has a lithofacies-breaking discordant basal surface. In contrast to the rest of the beds in the area it is very uniform in composition throughout the thickness and has very few body or trace fossils: the Crassostrea biofacies and the Ophiomorpha -Caegichnus and Caegichnus group ichnofacies occur once each.

(iii) In the Zelten sections calcareous sandstone and sandy limestone units on average 2.5 metres thick are interbedded with intertidal deposits, limestones and their associated shales. Most of them occur near the bases of the sections where they are typified by the Crassostrea, Placenta and mixed Crassostrea/bivalve-gastropod biofacies all indicative of shallow water brackish conditions. They die out laterally within a few hundred metres usually, depending upon the thickness.

Geographic distribution: Estuarine channel calcareous sandstones are widespread throughout the sections. They are especially common in the Jebel Zelten and Zelten sections , but scattered channels are found in the Marada and Raguba sections.

Environment: The small channels of (i) type represent the estuarine portions of fluvial channels cut through coastal and fluviatile environments. They contain mixed marine and continental biofacies characterised by great fluctuations in salinity and high current activity. They are clearly intertidal, and probably supported a rich algal growth.

The larger (ii) type channels have the geometry and internal structure of large estuarine distributory channels. Oomkens and Terwindt (1960) described rhythmic stratification from the Haringvliet Estuary in Holland. In a total thickness of 20 metres one or more fining upward sequences occurred:-

Top: Horizontally bedded rippled sand and clay. The beds are laminated or streaky and shell beds and peat are present.

Base: Crossbedded sands with clay laminae and beds, clay pellet conglomerates, shell beds and peat.

The complexity of the sequence reflects migrating interlaced channels and submerged elongate shoals. It is clearly very similar to the pattern in the large channel at the top of the Jebel Zelten, which probably therefore represents a large tidal estuarine channel built out between intertidal and subtidal calcareous sandstones and shales. The calcareous sands represent subtidal deposition, while the interbedded material is probably in part intertidal.

The calcareous sandstone channel at Raguba is not of this type.

Type (iii) the impersistent calcareous sandstones in the Zelten sections with the biofacies that indicate normal marine conditions subject to periodic influxes of brackish or fresh water, were deposited at the mouths of estuaries. A series of shallow sand ribbons mark the position of distributory channels cut into calcareous sands and shales and interlaminated sands and shales. Though the depth varied down to 10 m., many were radiating intertidal shoe-string sands such as occur off many estuaries today. The depositional rate and the current activity were periodic, and moderate to high. Selley (1967) recorded a bimodal, but typically northward dip of the crossstratification. He suggested alternating periods of dominant seaward transport (i.e. fluvial action) followed by lengthy landward reworking by wave action, such as migh be expected from areas associated with marked seasonal variation in rainfall

e.g. the Savannah.

Unconsolidated Deposits (Fluviatile beds of Selley)

A) Sands (55 units)

Description: Ill-sorted unconsolidated sand units, on average 5 metres thick occur in the lower halves of the Marada and Jebel Zelten sections. They are usually white, but may be yellow, mottled red and yellow, or green. Most of the sands are very pure but a few silty inter - laminae occur throughout some beds. At the base of section 23 the sands are cemented by silica to form a quartzite. Cross bedding very largely of festoon type, is commonly developed (62%), while horizontal bedding occurs in only 11% of the units. Ferruginous staining results in mottled sediment in many cases, discrete iron rich concentrations resembling ballstones being present in some beds.

Thin calcareous horizons present near the tops and bases of many units may be burrowed by marine ichnofacies.

Fossils occur in insignificant quantities in 38% of the units, the only biofacies represented being the continental one. Burrowing occurs in 27% of the units and other than two occurrences of marine types (the Ophiomorpha-Caegichnus and Caegichnus ichnofacies) in the carbonate bands, is by the rootlet cast ichnofacies.

Selley (1967) recorded a unimodal northwesterly dip in the cross - stratification, indicating shoreward currents.

Geographic distribution: Unconsolidated sands are very common in the lower parts of the sections on the south side of the Jebel Zelten and near Marada. Some of the Raguba and northern Jebel Zelten sections contain them, and there is one occurrence at the base of a Zelten section.

Environment: The lack of carbonate material and the presence of continental fossils and root traces indicates that these sediments were laid down on land. Pure illsorted crossbedded and horizontally bedded

sands are similar to the point bar deposits of fluvial channels (see Allen 1965), where deposition is periodic and current activity is high (upper portion of lower flow regime). The presence of abundant tree debris and crocodile and turtle bones indicates that the channels were rather similar to the densely forested rivers of the tropics (e.g. the Mississippi).

The sand units are up to 15 metres thick and may in some cases comprise the deposits of several fluvial channels. The preponderance of sands over their associated shales suggests the streams were of low sinuosity with wide and illdefined levees (Allen 1965).

B) Silty Shales (38 units)

Description: Laminated silty green gypsiferous shales overlying unconsolidated sands in over half their occurrences (55%), comprise units on average 2·65 metres thick.

Thin rippled sandy interlaminae up to 0·3 cm thick with well rounded clay pellets are very common throughout 42% of the beds. Lignitic or ferruginous material is locally abundant, and many of the units contain gypsum on the fracture surfaces (37%)

Slightly calcareous horizons occur in some units, in one case containing a surface covered in plant scrape markings.

Fossils, represented by leaves and gastropods belonging to the continental biofacies occur in 18% of the units, while burrows of the rootlet cast ichnofacies occur in 23% of the units.

Geographic distribution: Shales associated with calcareous sands are commonest in the lower parts of the Marada sections and on the south side of the Jebel Zelten. They are rarely found on the north side of the Jebel Zelten and never in the Raguba, Zelten and Zaggut sections.

Environment: The silty shales usually overlie sands interpreted as the point bars and levees of fluvial channels and represent the topset beds or swale-fills of Allen 1965. The latter are up to five metres

thick and consist of well stratified sandy silts, clayey silts and silty clays rich in lignitic material. Probably the thicker units (8 metres) represented by relatively uniform silty clays with frequent sandy interlaminae and rich in lignitic material, leaves and fresh water molluscs are flood basin deposits.

CHAPTER 7

GEOLOGICAL HISTORY (enclosures 2,3)

The Marada Sections (1 to 4) (figure 7.2)

The Marada sections comprise about 130 metres of sediments marking a transgression. The lower parts of sections 1 to 3 are composed of an alternation of thick fluviatile sands and thin calcareous sandstones representing brief intertidal transgressions up fluvial channels. Correlation between sections 2,3, and 4 is by means of a clay pellet conglomerate in calcareous sandstone rich in vertebrates and bivalves. Throughout the lower half of section 4 thick intertidal sands and inter - laminated sands and shales occur at the same level. Clearly therefore there was a shoreline in the neighbourhood of section 4 (the north east) when fluvialite sediments were being laid down farther to the south west.

The middle parts of the sections consist of thick shales and in - terlaminated shales and sands totalling nearly 30 metres, bioturbated throughout by the Ophiomorpha, Thalassinoides and Ophiomorpha - Caegichnus ichnofacies. Thick intertidal successions composed dominantly of shales do not occur anywhere else in the Zelten area, and evidently indicate an environment protected from strong current activity. The brackish water smooth bivalve, Capsa and Corbula basteroti biofacies are common throughout, so probably an algal-rich tidal lagoon was present. Intertidal limestones and sandy limestones are interbedded.

The tops of the sections comprise 35 metres of variable limestones; the lower parts of which are impure calcarenites containing numerous lime mud conglomerates and heavy bioturbation, especially by Thalassin - oides. Shell beds composed of the spherical calcareous algae, smooth bivalve-turreted gastropod, turreted gastropod and mixed calcareous

Key to geological history figures.

LITHOLOGICAL TYPES

- limestone
- sandy limestone
- shales
- calcareous sands & interlaminated units
- sands

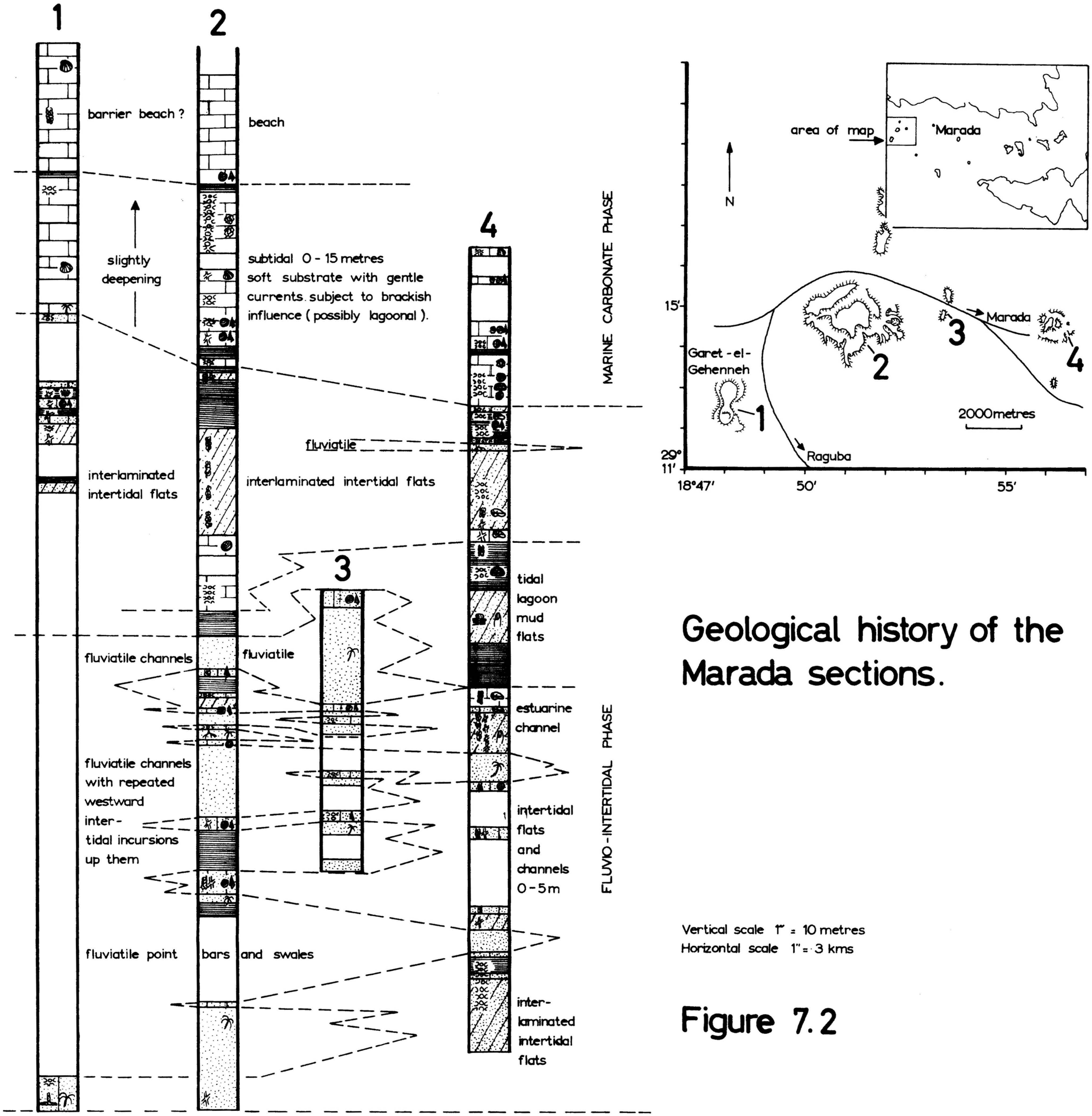
BIOFACIES (right side of sections)

- Trigonopora
- subfimbriata
- spherical calcareous algae
- Vermetus
- Lopha
- Echinolampas
- Crassostrea
- Placenta
- Idmonea
- mixed calcareous algae/Crassostrea
- smooth bivalve-turreted gastropod
- smooth bivalve
- turreted gastropod
- calcareous algae/bivalve-gastropod
- mixed Crassostrea/bivalve-gastropod
- ribbed bivalve
- Capsa
- Corbula basteroti
- Callianassa
- continental

ICHNOFACIES (left side of sections)

- Ophiomorpha
- Thalassinoides
- Ophiomorpha/Caegichnus
- Thalassinoides/Caegichnus
- Diplocraterion
- U Corophioides
- Argillites
- Caegichnus group
- Aestites
- rootlet cast

Figure 7.1



Geological history of the Marada sections.

Vertical scale 1" = 10 metres
Horizontal scale 1" = 3 kms

Figure 7.2

algae and bivalve-gastropod biofacies are common throughout and indicate shallow algal rich (0 - 15 metres) environments subject to strong currents in which there was fluctuating and rapid deposition and erosion. At the tops of sections 1 and 2 horizontally and cross bedded limestones with highly fragmented fossils and rare bioturbation by Ophiomorpha possibly represent a high energy beach environment.

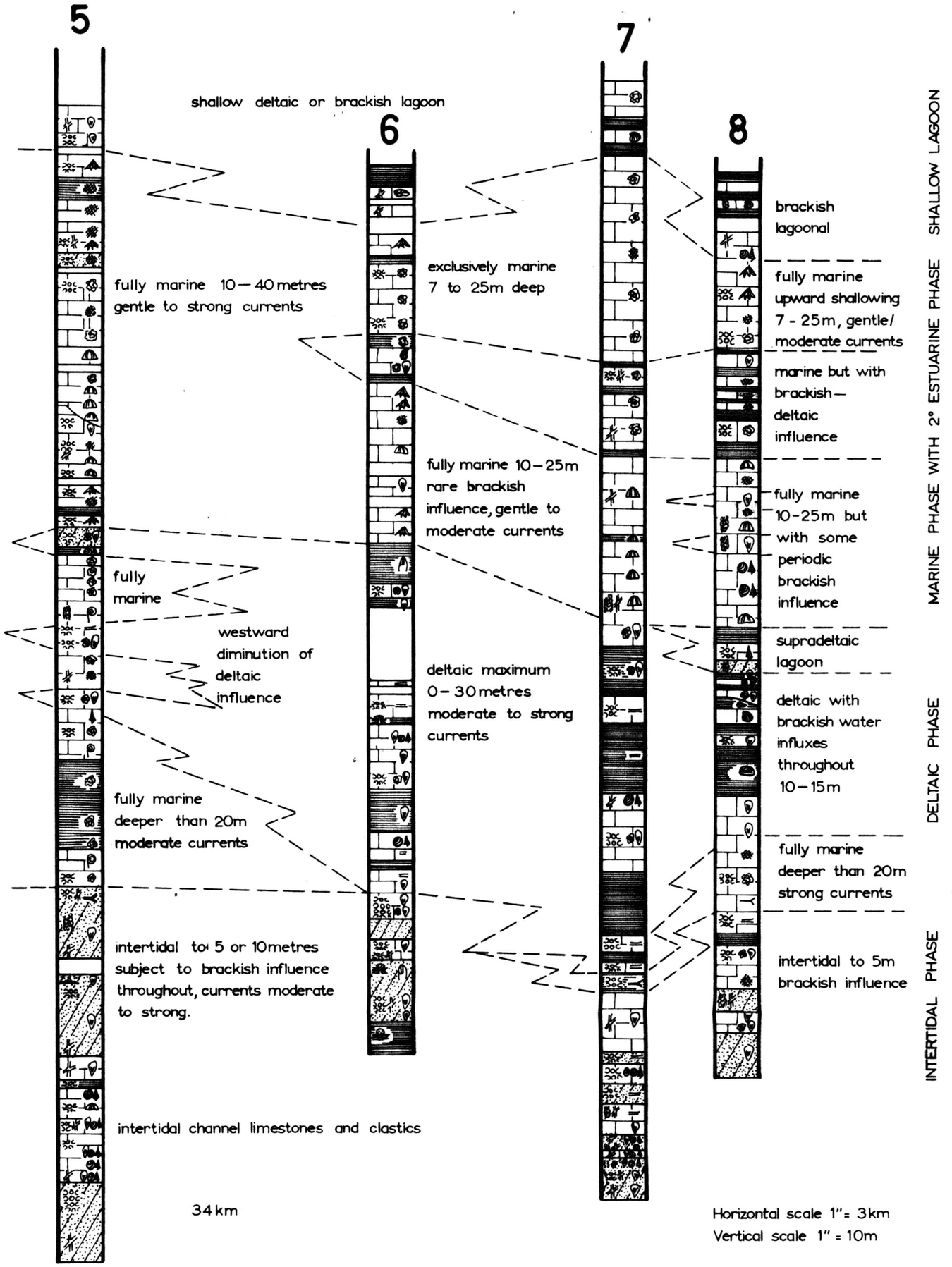
Summarising, a period of fluviatile and intertidal deposition was followed by the widespread establishment of intertidal flats and lagoons. A marine transgression marked by shallow limestone environments subject to periodic erosion by brackish-water channels proceeded, and culminated in a high energy beach environment.

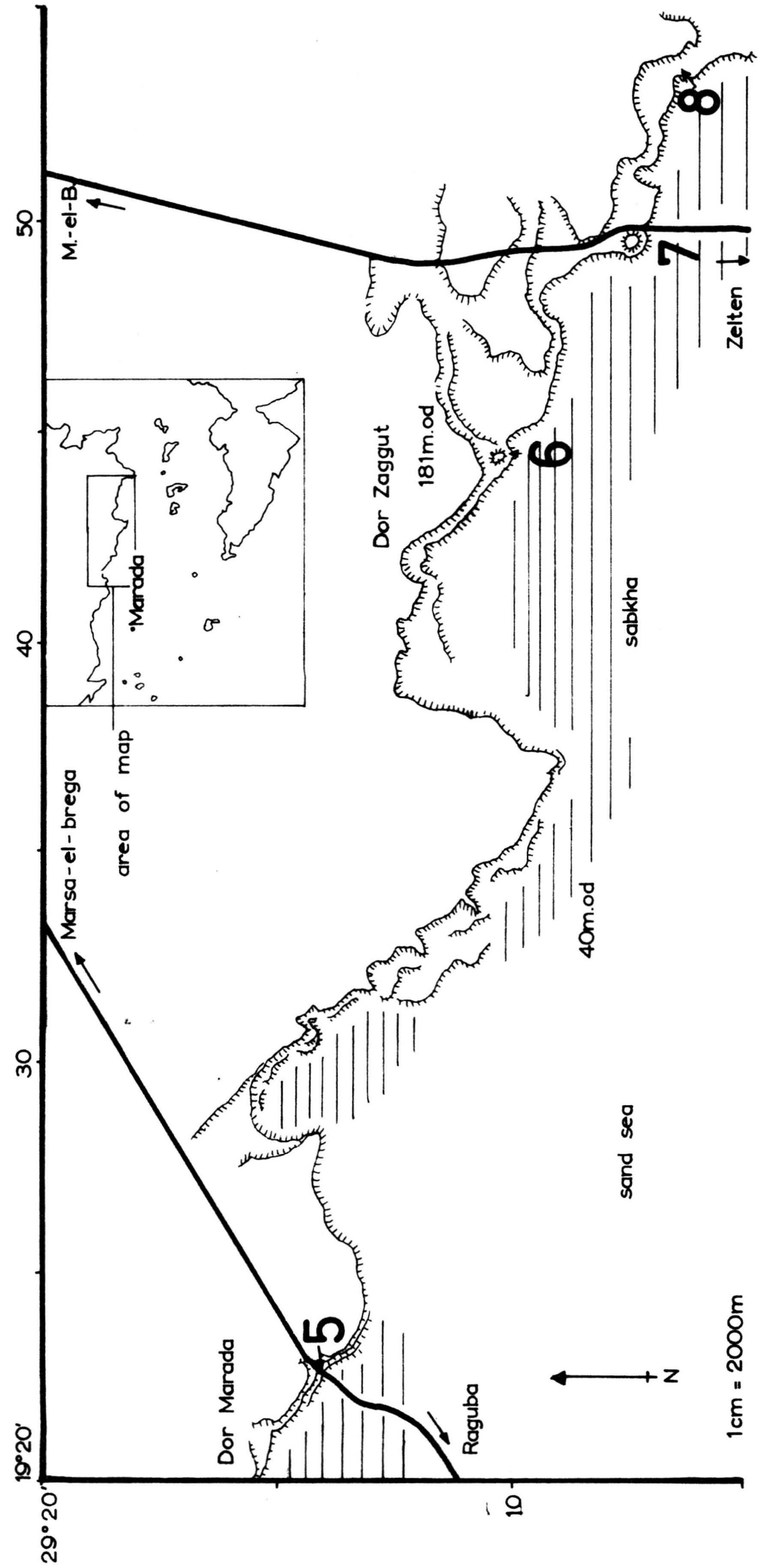
The Zaggut Sections (5 to 8) (figure 7.3)

There are two horizons in these sections that enable correlation: one is a richly fossiliferous bed near the bottom containing Idmonea atlantica, and the second is a series of beds near the middle rich in Echinolampas.

At the bases of the sections there is up to 35 metres of calcareous sand, interlaminated sands and shales and calcarenites. They are highly bioturbated by the Thalassinoides, Ophiomorpha-Caegichnus, Thalassinoides -Caegichnus and Caegichnus group ichnofacies, indicating shallow water and intertidal environments (0 - 5 metres) subject to gentle to mod - erate currents. The fossils are dominantly represented by the Crassostrea, Placenta and mixed Crassostrea/bivalve-gastropod biofacies, showing mixing of shallow water brackish and marine elements. In some of the crossbedded calcarenites channel deposits occur (figure 6. 1), and at section 5 the fully marine Lopha biofacies is present.

Up to 40 metres of thick limestones and shales follow, characterised throughout by fossils (e.g. the Crassostrea and Placenta biofacies) indicating periodic brackish influxes into marine water. Ichnofacies are rather uncommon and are not depth specific. The thickest shales





Geological history of the Zaggut sections

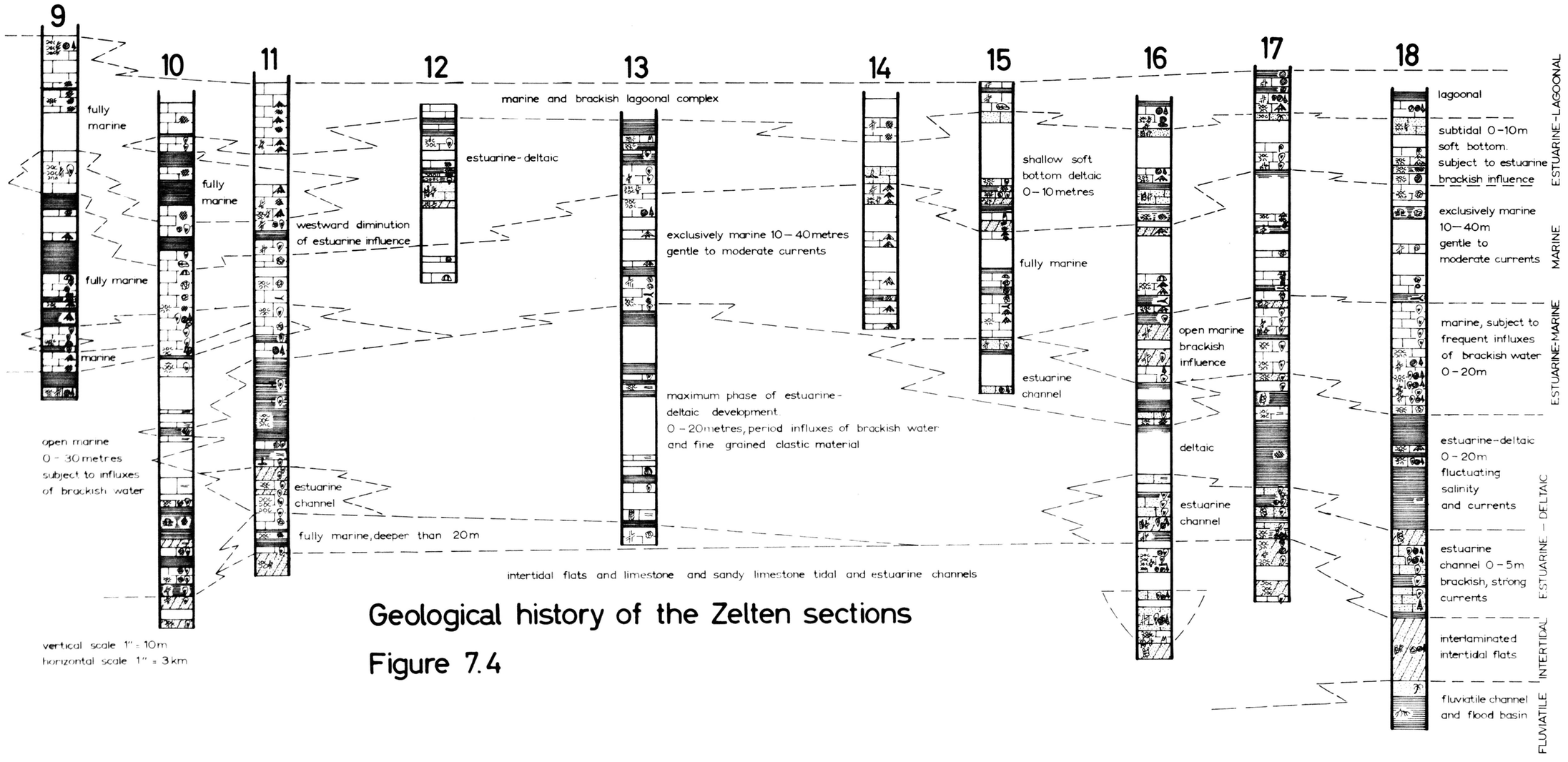
Figure 7.3

occur in sections 6 and 7, where deposition in depths of 0 to 30 metres with moderate to strong currents took place. This represents the sub - tidal portion of the estuary farther south (see Zelten sections). In sections 5, 7, and 8 a thin bed or beds containing the Idmonea atlantica horizon occur at the base and represent fully marine deposition in depths of over 20 metres before the development of the estuary. Indeed, throughout this portion of section 5 though thin shales are present, most of the biofacies are fully marine (1,4,3). It is clear that the influence of the estuary waned westwards.

The brackish water biofacies are replaced in the 40 metres of limestone above, by the fully marine types Trigonopora, spherical calcareous algae, Lopha and Echinolampas. These indicate deposition in depths 10 to 50 metres in areas of variable (gentle to strong) current activity. Near the middle of this portion in sections 6,7, and 8 thin shale beds occur and in sections 6 and 8 there are a few units with brackish biofacies, These mark the influence of the second period of estuarine development (see Zelten sections). At the top of this portion there are signs of shallowing, the Lopha and smooth bivalve-turreted gastropod biofacies occurring with the Caegichnus group ichnofacies. This phase culminates in the very shallow or intertidal 10 metres of limestones and shales at the top of the successions. These are burrowed by the Caegichnus group and Ophiomorpha ichnofacies and contain the brackish ribbed bivalve and Capsa biofacies. They probably represent brackish lagoonal deposits. The best correlation between these and the Marada sections is between the tops of the intertidal portions.

The Zelten Sections (9 - 18) (figure 7. 4,5)

Correlation in these sections is also by two horizons, but they are usually within two metres of each other near the middle. The lower



Geological history of the Zelten sections

Figure 7.4

one consists of a silty limestone or calcareous siltstone crowded with Idmonea fenestrata, while the upper one contains abundant Echinolampas . Correlation with the Zaggut sections is therefore easy.

As in the latter the basal deposits in these sections are lime - stones and interlaminated shales and sands with brackish water biofacies. The ichnofacies indicate they are intertidal, and at section 18 they overlie fluviatile deposits. At section 16 crossbedded calcareous sand - stones and sandy limestones with mixed biofacies mark the position of an estuarine channel.

There follows up to 30 metres of alternating shale and limestone units dominated by the Crassostrea and Placenta biofacies. These sedi - ments represent the intertidal and subtidal portion of the estuary, the shales being rather thicker than in the corresponding portions of the Zaggut sections. At various levels estuarine calcareous sandstones with the Crassostrea biofacies are present. They are clearly not all the same channel, for instance there is one at the base of this part of the section in sections 16, 17 and 18, and one at the top of sections 15 and 16. As in the Zaggut sections there are fully marine units with Idmonea atlantica at the base in some sections (11 and 13). In the westernmost and easternmost sections the shales die out rather earlier than in the centre and up to 15 metres of limestones dominated by brack - ish biofacies and very shallow subtidal or intertidal ichnofacies (Caegichnus group and Ophiomorpha-Caegichnus) occur.

Fully marine limestones, characterised by the spherical calcareous algae, Lopha,Echinolampas and Idmonea biofacies follow, but are never more than 20 metres thick. In the Zaggut sections the Echinolampas biofacies may occur through 15 metres of section, but in the Zelten area Echinolampas rarely occurs in more than one unit, a metre thick. There is therefore, considerable reduction in this portion of the succession southwards. These beds are overlain by a second development

Locations of the Zelten sections.

Figure 7.5

of estuarine sediments with the Crassostrea and spherical calcareous algae / Crassostrea biofacies. Small calcareous sandstone channels with intertidal Ophiomorpha-Caegichnus bioturbation are widespread. Many of the closely associated beds, however, contain fully marine biofacies so evidently this period of estuarine development was not as widespread as the first.

The tops of the sections are composed of fine grained limestones and thin shales with shallow water Caegichnus group bioturbation and soft substrate brackish water biofacies (ribbed bivalve, Capsa), possibly representing lagoons.

The Raguba Sections (19 - 24) (figure 7. 6)

The lower parts of these sections consist of an alternation of fluviatile sands and intertidal beds throughout characterised by the Ophiomorpha, Ophiomorpha-Caegichnus and Caegichnus group ichnofacies. The thickness of interlaminated shales and sands suggests the environ - ments correlate with the central lagoonal portion of the Marada sections.

At sections 22, 23 and 24 a maximum of 20 metres of very shallow water and intertidal calcarenites occur, highly bioturbated by the Ophiomorpha, Thalassinoides and Ophiomorpha-Caegichnus ichnofacies. A number of shallow water, but generally fully marine biofacies are represented. A variety of environments were probably developed, at 23 shallow nearshore carbonate banks were present, while at 24 most of the beds are very highly bioturbated and probably intertidal.

The succeeding beds, consisting of 65 metres of green shales with thin limestones, are only present in section 24. They represent the shallow subtidal and intertidal portion of the estuary (see Zelten and Jebel Zelten sections), the bioturbation in the limestone interbeds indicates that intertidal or very shallow water conditions prevailed

Geological history of the Raguba sections

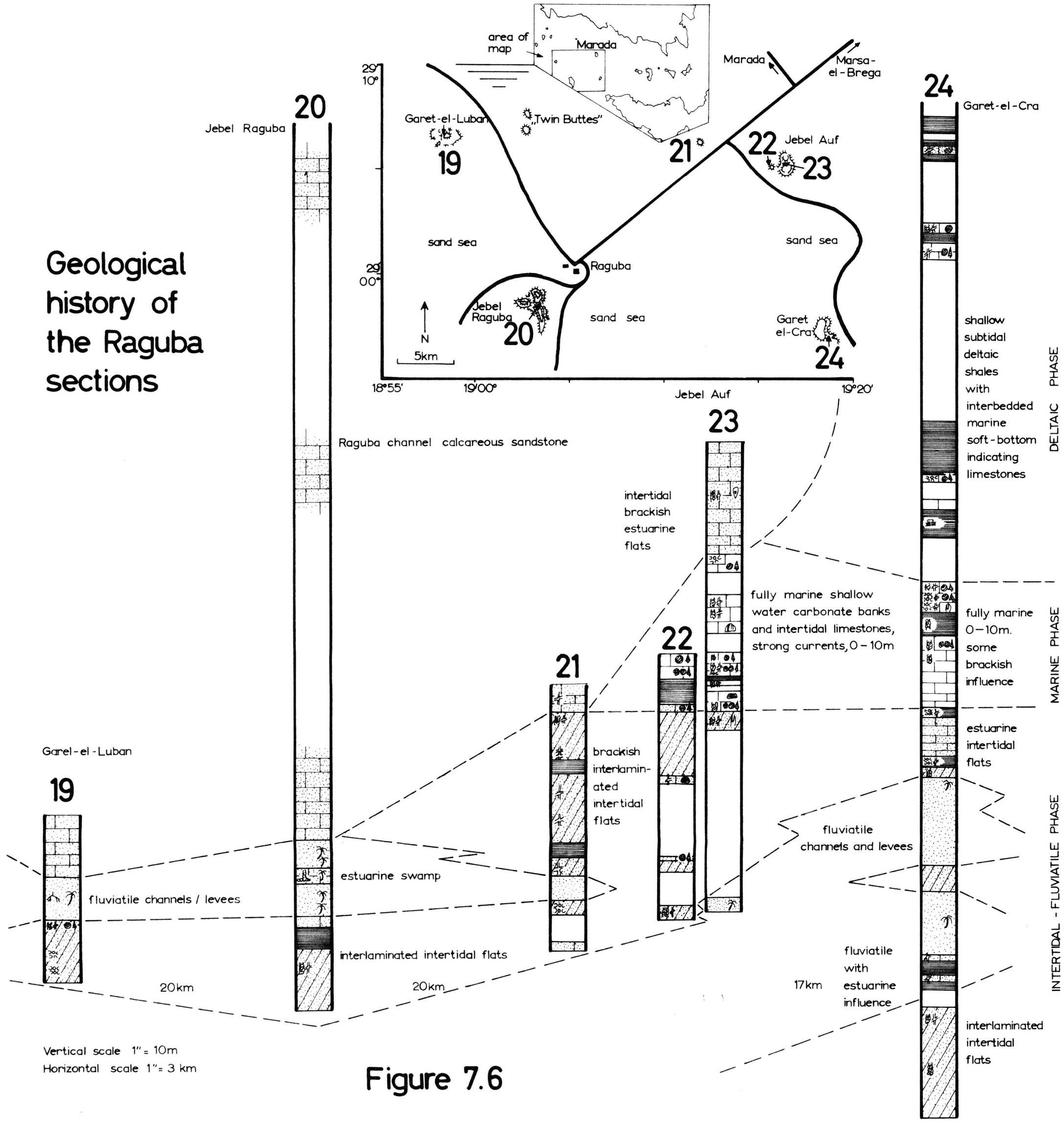


Figure 7.6

throughout. The biofacies do not indicate low salinities, so probably these shales were deposited well away from a distributory, in part in protected intertidal flats and lagoons.

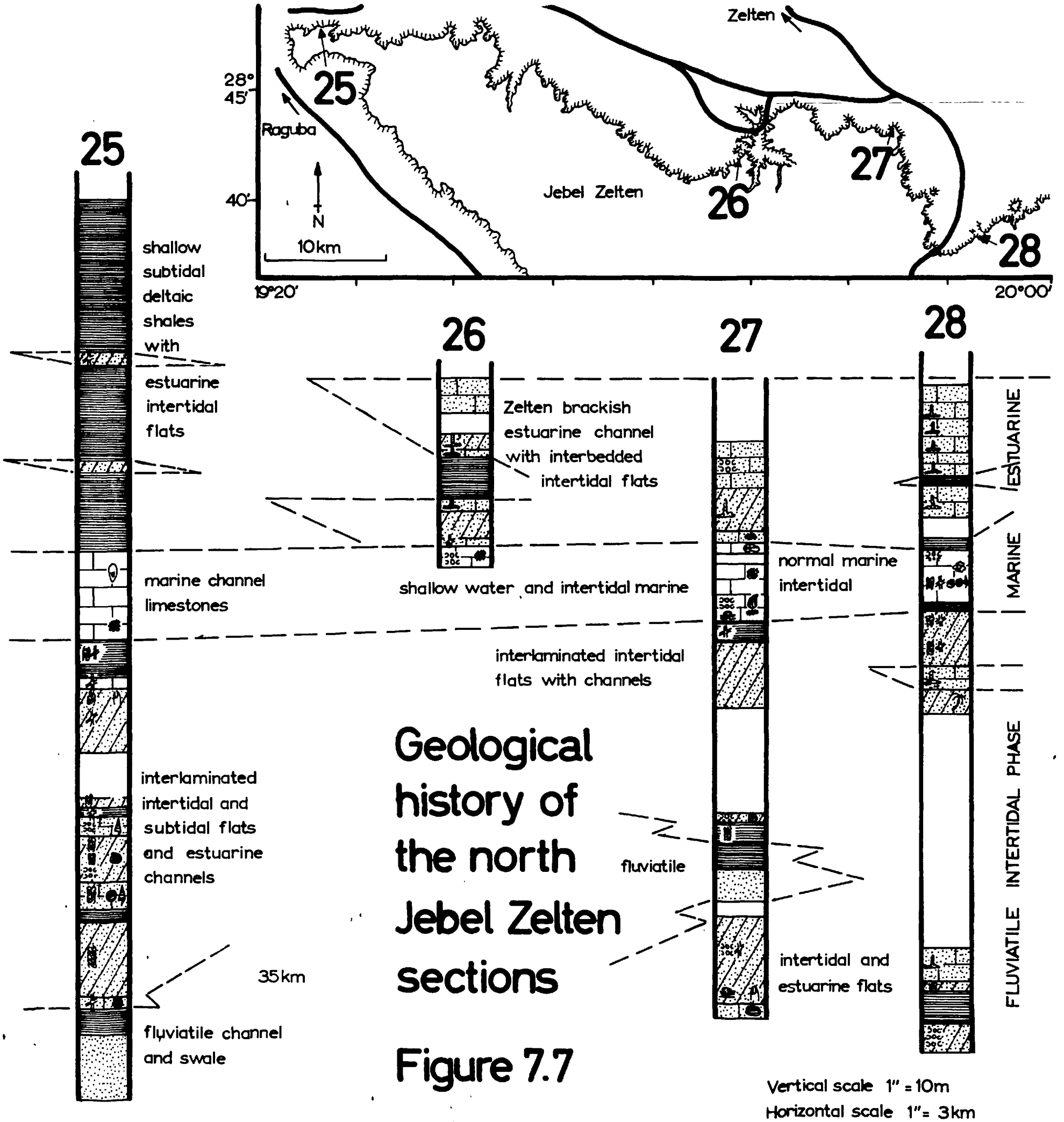
The limestones in the middle of the sections may be correlated with the intertidal limestones at the base of section 5, the Echinolampas ichnofacies being present in a bed both there and at section 23. The bed in both cases contains Holoporella fabianii a species that occurs nowhere else in the Zelten area.

At the tops of sections 19 to 23 a crossbedded calcareous sandstone with a maximum thickness of over 150 metres occurs. At sections 19 and 20 it overlies fluviatile sands, at section 21 intertidal beds and at section 23 limestones. Its basal surface is therefore strongly facies discordant. It is very poorly fossiliferous, containing the Crassostrea biofacies and the Ophiomorpha-Caegichnus ichnofacies once. Selley (1968) regarded it as an estuarine channel rather like they are farther east (see Zelten sections) but its markedly uniform composition (in strong contrast to the rest of the sediments of the area) and strongly discordant base suggest that it is a later deposit, not related to the deposition of the Marada group. It is never overlain by anything and does not interfinger with any of the other sediments of the area, so it is impossible to date.

North Jebel Zelten Sections (25 - 28) (figure 7. 7)

As at Maguba, the basal beds of these sections consist of intertidal and fluviatile deposits, though the latter are rather unimportant.

The limestones in the centre of the sections are less than 10 metres thick and consist of shallow subtidal and intertidal calcarenites and calcisiltites. Bioturbation by the Ophiomorpha and Thalassinoides ichnofacies is common, especially at section 28, and normal marine biofacies occur throughout. At section 25 the limestones are crossbedded and conglomeratic and possibly represent a channel. This portion of



Geological history of the north Jebel Zelten sections

Figure 7.7

Vertical scale 1" = 10m
Horizontal scale 1" = 3km

the sections clearly corresponds to the calcarenites in the intertidal portion near the bases of the Zelten and Zaggut sections.

In sections 25 and 26, shales and interlaminated sands and shales with calcareous sandstone interbeds overlie. They correspond to the shales towards the top of the Gabet - el - Cra section (24) and represent subtidal and interdistributary shales related to the estuarine channels.

The top part of all the sections consists of the large Zelten estuarine distributary channel referred to in the preceeding chapter. It is composed of crossbedded calcareous sandstones, bioturbated by the Aestites ichnofacies with thin interlaminated interbeds.

The South Side Jebel Zelten Sections (29 - 39) (figure 7.8,9)

The lower parts of the succession consist of a maximum of 130 metres of alternating intertidal and fluviatile sediments. Throughout, cycles of fluvial channel sands with the continental ichno- and biofacies passing up through swale-fill silts and shales into intertidal transgressions represented by calcareous sands and sandstones with the Ophiomorpha, Ophiomorpha-Caegichnus, and Caogichnus group ichnofacies can be recognised. Intertidal sands are much more common in these sections than in intertidal deposits farther north. This indicates that after fluviatile sedimentation had ceased in the area and carbonate deposition had started, there was little sand available. The coarse deposits of the intertidal zone were then represented by limestones (see Raguba and Zaggut sections). At various levels discordant cal - careous sandstone bodies up to 10 metres thick with the ribbed bivalve Corbula basteroti, and smooth bivalve-turreted gastropod biofacies (see sections 31, 32, 35), mark minor estuarine channels and at sec - tions 38 and 39 thick tidal channel deposits occur, cutting through other intertidal sediments.

Apart from a general tendency for fluviatile deposits to decrease

29

30

31

32

33

34

35

36

38

39

37

brackish intertidal

intertidal with tidal channels, some brackish influence

fluviatile channels with intertidal interbeds representing incursions up existing fluvial channels

23km

Vertical scale 1" = 10m
Horizontal scale 1" = 3km

minor estuarine channels cut into fluviatile and intertidal sediments

repeated cycles of fluviatile channel sands passing up into swale-fill shales and then into calcareous sands and sandy limestones representing incursions of intertidal environments. the latter may cover the fluviatile sediments or fill existing fluvial channels.

calcareous sandstones and interlaminated beds of the Zelten estuarine channel

brackish intertidal and subtidal 0-5m with strong estuarine influence.
always calcareous, often represented by limestones

intertidal with tidal channels

dominantly fluviatile

brackish intertidal

ESTUARINE

SHALLOW MARINE

INTERTIDAL PHASE

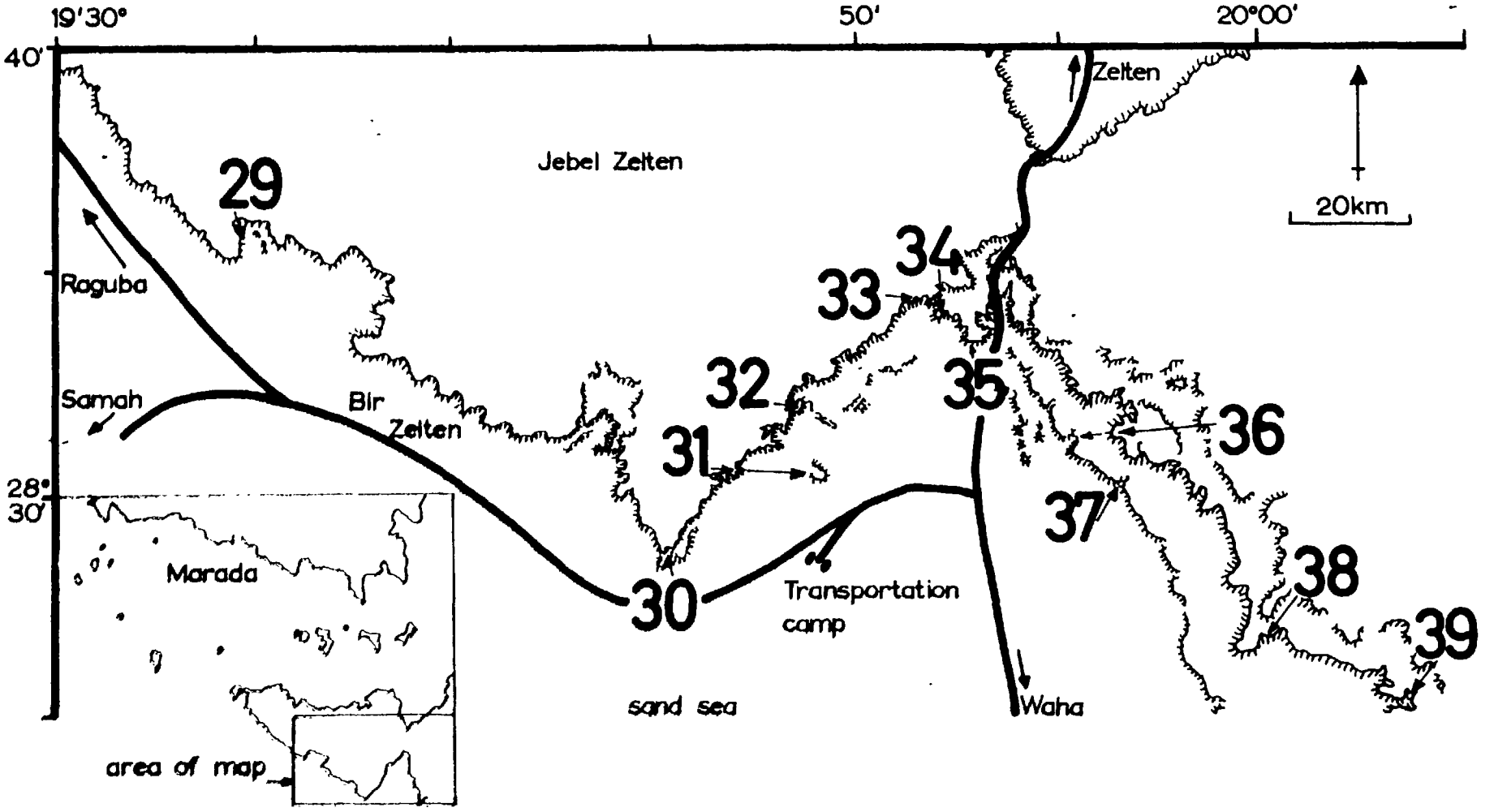
FLUVIATILE

Geological history of the southern Jebel Zelten sections.

Figure 7.8

Location of sections on the south of the Jebel Zelten

Figure 79



upwards, no succession can be recognised in the lower parts of the successions.

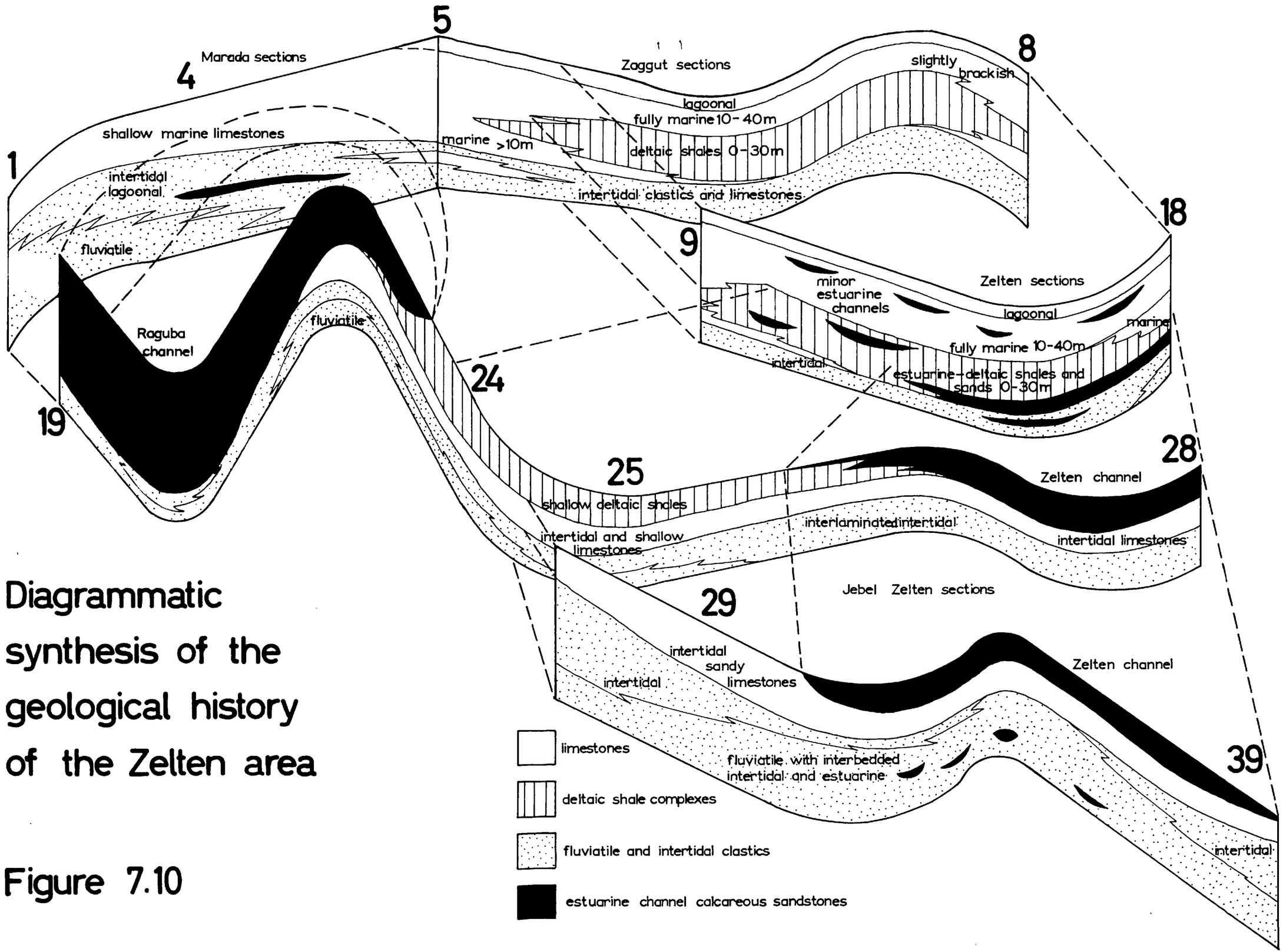
Up to 25 metres of intertidal calcareous sandstones, sandy lime - stones and limestones with interbedded shales follow. Throughout, they are highly bioturbated by the Ophiomorpha, Ophiomorpha-Caegichnus, Caegichnus group and Aestites ichnofacies, and contain the marine or brackish intertidal biofacies - turreted gastropods, ribbed bivalve, Corbula basteroti and continental biofacies. They are the equivalents of the limestones in the central parts of the sections to the north, so the biofacies probably indicate normal marine sand and mud environments. The synclinal attitude of these beds is possibly due to syn-sedimentary subsidence (Selley 1968).

At the tops of all the sections except for 29 there are up to 20 metres of crossbedded calcareous sandstones and interlaminated beds. They represent the deposits of the large estuarine distributory channel present on the north side of the Jebel Zelten and towards the bases of the Zelten sections. Selley's (1968) correlation of this channel with the calcareous sands near the tops of the Zelten section is not accepted.

Environmental History of the Whole Area (figure 7. 10)

A) The Earlier Phase (figure 7. 11)

Limestones and shales, similar to those of the Zaggut sections but crowded with large Nummulites occurring below the bases of sections 1 and 19 mark the close of the Oligocene. They were followed throughout the area by a period of nearshore continental deposition characterised by fluviatile and intertidal sands and shales. The dip of these beds carries them from the middle of the Marada and Jebel Zelten sections to the bases of the Zelten and Zaggut sections. There is clearly a dip to the northeast that is accentuated by the change in



Diagrammatic synthesis of the geological history of the Zelten area

Figure 7.10

topographic height southwards across the area (see sections). There is a marked increase in intertidal sediments northwards and eastwards so the shoreline lay in the same direction. A slight transgression is indicated by the upward decrease in fluviatile deposits. Impersistent estuarine and tidal channels are distributed through the sediments of this period. The thickness and extent of the intertidal deposits is due to lengthy periods of relative stability when progradation took place.

B) The Later Phase (figure 7. 12)

A period of much more marine deposition marking the close of dominantly clastic deposition and the onset of limestone deposition then took place. Probably the marked drop in clastic supply was due to a general reduction in topography and efficiency of the streams. Reworking of the underlying sediments in an intertidal or very shallow brackish water environment produced the alternating calcareous sandstones, sandy limestones and shales of the Jebel Zelten. To the north these beds are of variable thickness, always very shallow water, and charac - terised by both fully marine and brackish water biofacies.

The close of this period is marked in the north by a thin band of inwashed deeper water biofacies.

The major period of carbonate deposition followed, but is repres - ented only in the Marada, Zaggut and Zelten sections. It was charac - terised by depths of 0 - 40 metres in clear open water. To the south, a very large estuary developed in the Jebel Zelten area, depositing shales as far north as the Zaggut sections. Calcareous sandstones with a brackish water fauna marking the position of distributory channels occur at different levels throughout this period near Zelten. Widespread shales representing a number of intertidal and shallow water environ - ments, such as the subtidal portion of the estuary, mudflats,

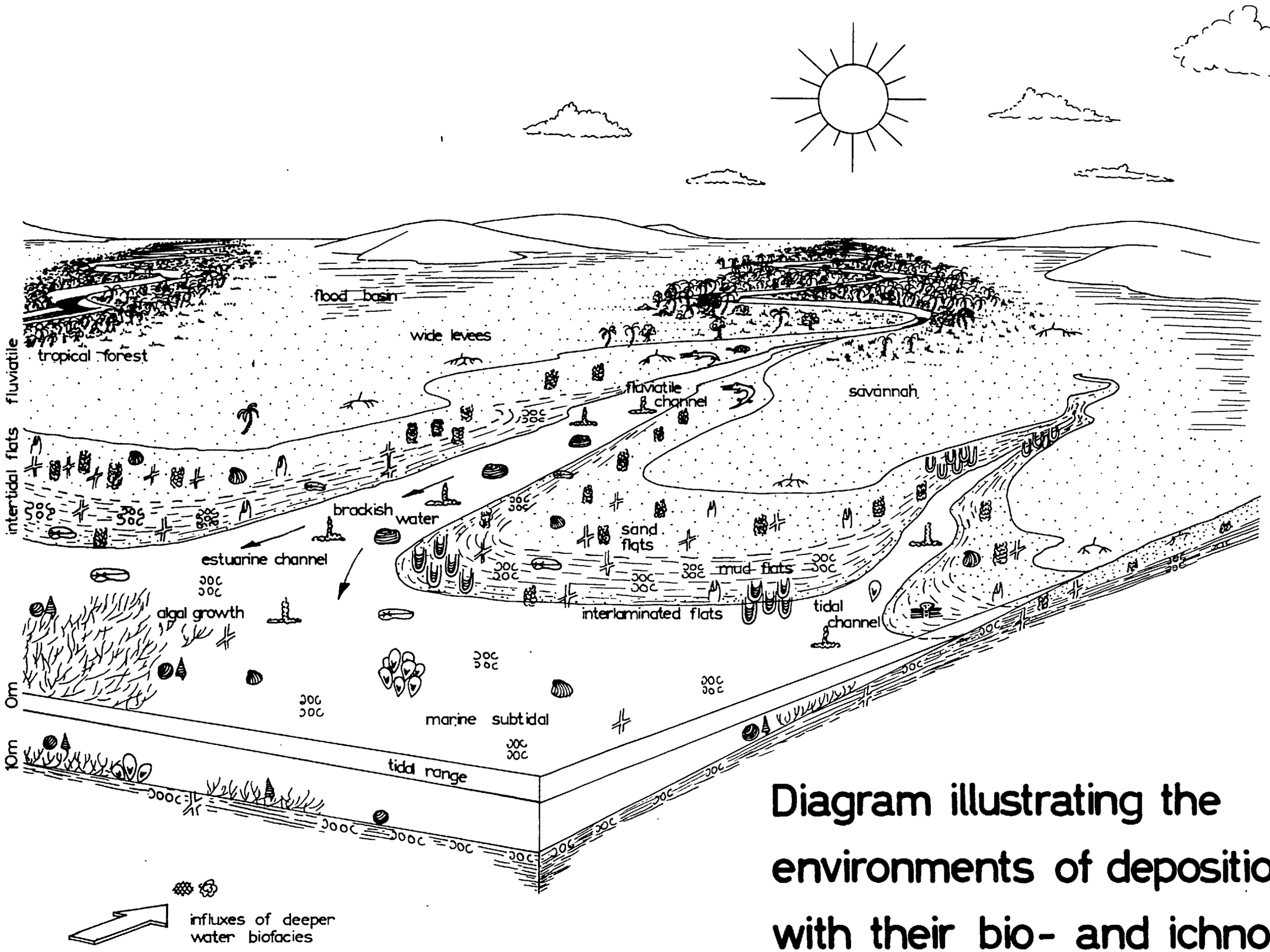


Figure 7.11

Diagram illustrating the environments of deposition with their bio- and ichno-facies in the early phase.

interdistributory areas, and lagoons occur in the Zaggut, Zelten, Raguba and North Jebel Zelten sections. They are all characterised by brackish biofacies with or without marine influence. Crassostrea gryphoides reefs developed in nearshore areas where there were regular influxes of fresh or brackish waters, as in the Mississippi delta area (Kolb and Van Lopik 1966). The influence of the estuary waned westwards, and at section 5 there is little evidence of its influence.

A further transgression destroyed the estuary and a period of completely marine deposition in depths of 10 - 50 metres characterised by the presence of Echinolampas took place. These parts of the sections are only represented in the Zaggut and Zelten sections and were either never deposited or have been removed from the areas to the south - there is a conglomerate at the base of the overlying limestone in the Jebel Zelten. Probably the latter is the case, as a second period of mixed clastic and carbonate estuarine development followed as the water became shallower. It was very much less important than the first, being represented in the Zelten sections by minor channel deposits and a few shale beds, and in the Zaggut sections by a few shales only. The period of regression finished with the development of bays and lagoons com - posed of limestones with brackish water biofacies.

Because of their monotonous composition and transgressive base, the calcareous sandstones of Raguba are not thought to be related to this period of deposition.

The environmental history of the area describes a simple trans - gression of carbonate environments over pre - existing clastic shallow water and continental beds, followed by a regression consequent upon the sedimentation. The pattern is complicated by the development of estuarine complexes at two periods.

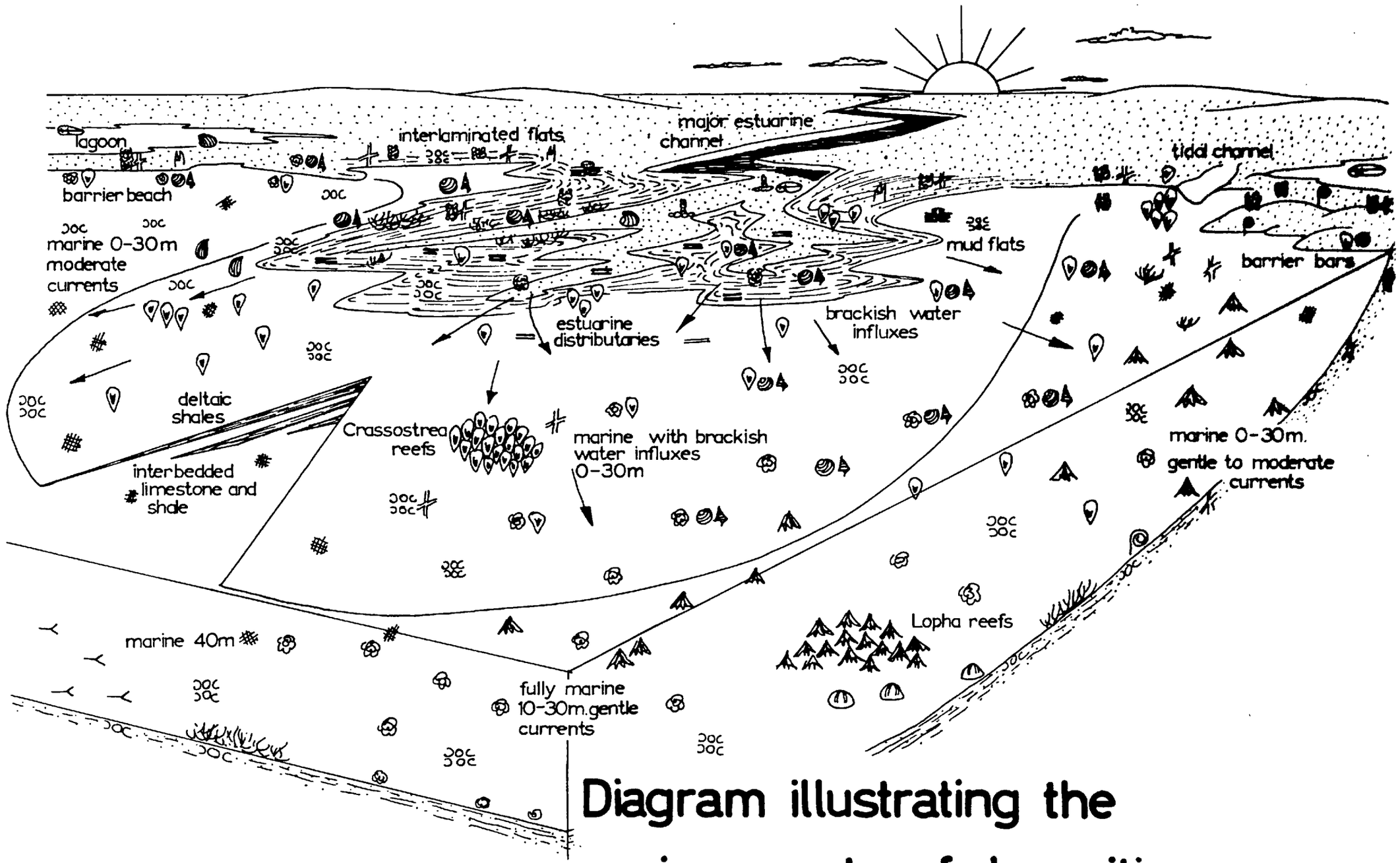


Figure 7.12

Diagram illustrating the environments of deposition with their bio- and ichnofacies in the later carbonate phase.

The Age of the Marada group

Desio (1935) considered that rocks of Aquitanian, Burdigalian and Helvetian age were present in the Marada area. He regarded the continental and shallow water sediments in the Garet - el - Luban section as Aquitanian, while in the limestones of Garet - el - Mazzala he found faunas belonging to both the Burdigalian (called by him Langianian) and Helvetian. In his map of the area, Desio referred the sediments on the south side of the Jebel Zelten to the Aquitanian, and Savage (personal communication) confirms that the continental mammal fauna from there is late Aquitanian or early Burdigalian. Selley (1968 in press) regarded the limestones of the Zaggut sections as Burdigalian on the basis of microfossils found in the limestones.

It appears therefore, that the earlier phase of deposition took place in the Aquitanian and early Burdigalian, while the later carbonate phase was deposited in the latter part of the Burdigalian and in the Helvetian.

Selley (1968 in press) took the thin limestone band at the top of most of the sections - the Fortine Limestone - as a marker horizon. However, as already mentioned, it overlies the Marada group conformably in the north, but unconformably in the south, and moreover, is not of consistent lithology, being much more sandy in the south. As much of the Burdigalian - Helvetian limestone succession seems to be absent from the south, it cannot be taken as a marker horizon for equating the sec - tions in the area.

Recent Analogues

The closest known analogues of these sediments occur in the Gulf of Mexico - the most completely described area of tropical recent sedi - mentation.

The limestones of the Zelten area were never deposited in water deeper than perhaps 50 metres, and yet they cover a very large area geographically. During the period of fully marine deposition for instance they were being laid down over a northeast - southwest distance of over 25 kms. A general inclination of between 7' and 8' assumes a drop of 50 metres in 25 kms. Probably this is a maximum figure - in most cases the distance will have been greater and the total water depth less. The inclinations of between 1' and 2' recorded by Gould and Stewart (1955) on the continental terrace of the N.E. Gulf of Mexico are of similar proportions. Comparison of the Zelten limestones with the recent sediments of that area is made difficult by the Pleistocene sea level changes affecting the latter that, for instance account for oolites in depths of over 40 metres. However, the areas are comparable in that clastic shoreline material is being reworked by erosion as the sea level rises to produce marly and sandy limestones mixed with the pure offshore limestones. In Charlotte harbour, Florida (Ter-chien Huang and Goodell 1967) for instance, a complex of estuaries and lagoons is developed: The bottom topography has been divided into:-

(i) Broad, shallow estuaries with central channels up to 6 metres deep connected to tidal channels in the harbour entrance.

(ii) Shallow lagoons, sands and grassy sand flats with numerous islands, deposited in 0 - 2 metres of water. The biota includes oysters, bryozoa, echinoids, corals, fish teeth, algae and worm burrows.

(iii) Slopes between (i) and (ii) deposited in 2 - 4 metres.

(iv) Tidal channels of sand between 4 and 25 metres deep.

A similar environmental distribution was noted in Tampa Bay, Florida (Goodell and Gorsline 1961) but clay was being deposited in the shallow lagoons and bays. The deposits were between 13 and 17 metres thick in the bays, but were over 30 metres thick in the tidal channels.

The carbonate percentage, less than 5% in the inner bays, was over 40% in the tidal channels.

The amount of silt and clay grade material is the main difference between the sediments of the Marada group and those in Florida. Between the distributory and tidal channels and in the area seaward of the es - tuary there are thick shale deposits representing a rudimentary delta.

Clay deposits associated with estuarine channels occur in the shallow water environments of the Mississippi delta. Scruton (1960) recorded mixed marine and continental material (wood and oysters) in the delta front silts and sands in depths of 3 - 20 metres. He also noted a gradual seaward decrease in sandy interlaminae in the shales.

Kolb and Van Lopik (1966) gave a review of the environments re - presented on the Mississippi delta. The fluviomarine environments include:-

(i) Prodelta clays, becoming gradually finer and more homo - geneous offshore,

(ii) Mudflats, formed where coarse material is scarce or absent.

(iii) Intradelta silts and clays.

(iv) Interdistributary deposits, mainly clays with sandy inter - laminae, grading downward into the prodelta clays.

The marine environments are represented by:-

(i) Bay Sound sands and silts, deposited in 2 - 3 metres of water partially protected by bars.

(ii) Reefs,:- of Crassostrea virginica developed in many near - shore areas where there are numerous influxes of fresh or brackish water. They are especially common in the partially protected bays.

(iii) Nearshore gulf deposits are associated with a transgressive sea. When the delta is abandoned in one particular area, they trans - gress over the sinking sea floor. The nearshore gulf deposits are frequently composed of coarser material than the delta (Scruton 1960).

The differences between the estuarine deposits of the Zelten area and those of the Mississippi delta are, of course, rather marked. A thick prodelta silt-clay sequence is absent and the offshore deposits are limestones. The tectonic styles of the areas are, however, different. The rocks of the Marada area were deposited on the edge of stable platform which throughout the period remained in very shallow waters. The Mississippi delta on the other hand is in an area of active downwarp (Murray 1960). It is not surprising, therefore, that the sedimentary succession at Zelten is very much thinner and that all of the rocks are shallower water. The savannah climate indicates that outflow of clastic material into the marine realm was periodic rather than continuous and the resultant alternating sequence of land derived shales and normal marine deposits is what might be expected.

Particular points of similarity are the variable estuarine and tidal channels, the interdistributary clays, the bay sound or lagoonal deposits and the Crassostrea reefs.

A parallel may be drawn between the Zelten area and the Mississippi only if the different styles of deposition are appreciated: clearly the rate of sedimentation was very much slower in the fossil example, so that the offshore deposits contained very little clastic material and consisted almost exclusively of fragmented shell debris, reworked shorewards and interdigitated with the clastic deposits of the estuary during periods of low outfall. The high percentages of suspension feeders indicate that during most of the period deposition was very slow or did not take place at all.

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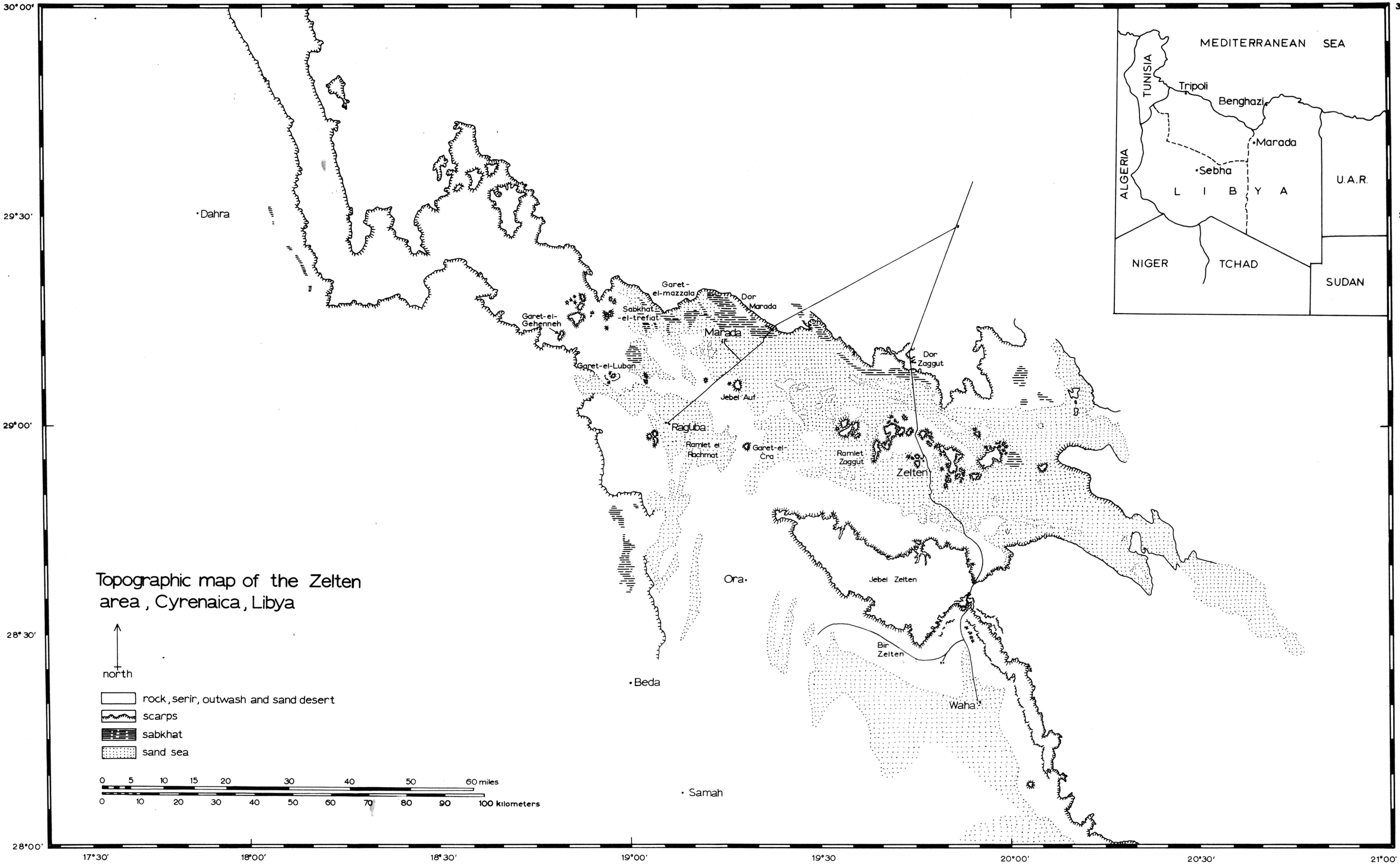
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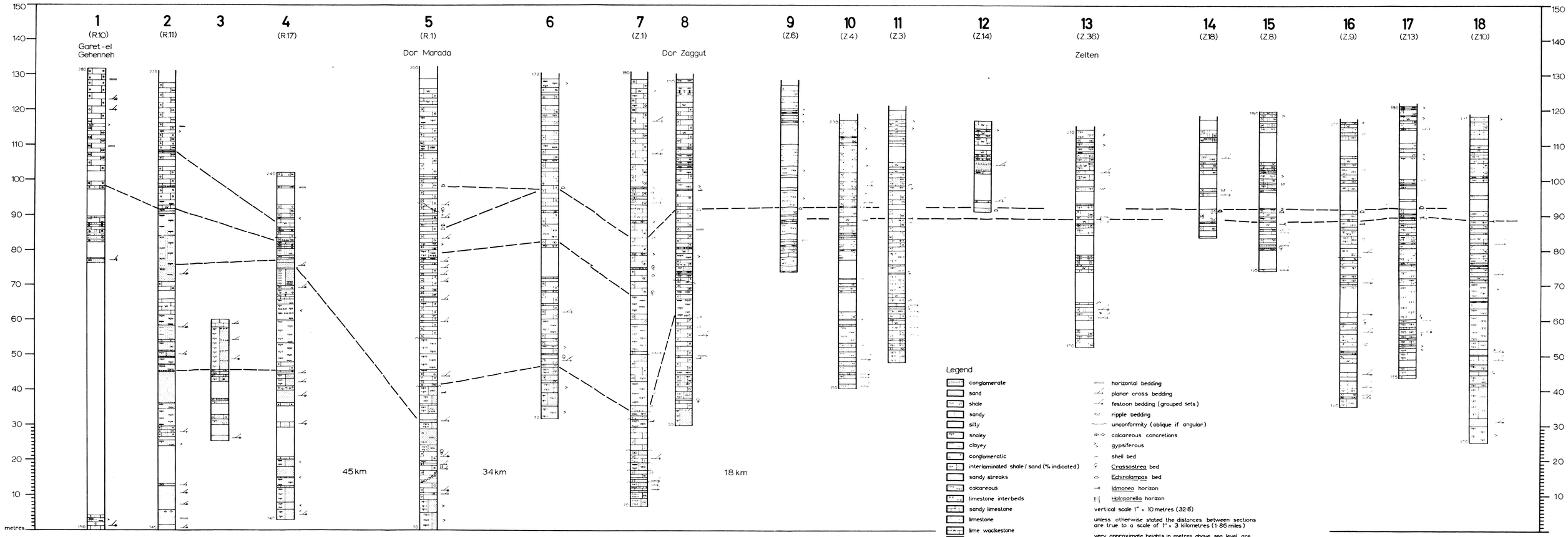
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Topographic map of the Zelten area, Cyrenaica, Libya



ZELTEN AREA, LIBYA

W-E MEASURED SECTIONS 1-18 ACROSS THE NORTHERN PART OF THE AREA



Legend

- conglomerate
- sand
- shale
- sandy
- silty
- shaley
- clayey
- conglomeratic
- interlaminated shale / sand (% indicated)
- sandy streaks
- calcareous
- limestone interbeds
- sandy limestone
- limestone
- lime wackestone
- calcisiltite
- calcarenite
- mixed calcarenite and calcisiltite
- conglomeratic calcarenite
- conglomeratic calcisiltite

- horizontal bedding
- planar cross bedding
- festoon bedding (grouped sets)
- ripple bedding
- unconformity (oblique if angular)
- calcareous concretions
- gypsiferous
- shell bed
- Crassostrea bed
- Echinolampas bed
- Idmonea horizon
- Holoporella horizon

vertical scale 1" = 10 metres (32·8)

unless otherwise stated the distances between sections are true to a scale of 1" = 3 kilometres (1·86 miles)

very approximate heights in metres above sea level are given on the left of the sections

the figures in parenthesis below the section number refer to sections measured by Selley (the section was not necessarily measured in exactly the same place)

the legend employed is the standard of the Royal Dutch / Shell Group.

ZELTEN, LIBYA. W-E MEASURED SECTIONS ACROSS THE SOUTHERN PART OF THE AREA

