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THE DISTRIBUTION AND ECOLOGY OF RECENT FORAMINIFERIDA OFF THE EBRO DELTA, NORTHEASTERN SPAIN.

by

Michael Edward Scrutton B.Sc.

A thesis submitted for the degree
of Doctor of Philosophy at the
University of Bristol.

VOLUME ONE

MEMORANDUM

The material presented in this thesis represents the results of research carried out in the Department of Geology, University of Bristol, between July 1966 and July 1969.

The thesis is based on my own independent research under the supervision of Dr. J.W. Murray and any previously published or unpublished work used by me is given full acknowledgement in the text.

M Boulton

July 1969

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ABSTRACT

The main purpose of the work was to carry out a detailed seasonal study of the distribution and ecology of the living benthonic foraminiferids in the different environments around the Ebro delta. As a background to the ecological work, a rough sedimentological examination of the Ebro delta itself was attempted.

The delta is relatively small, having a surface area of 330 sq. km., and discharge from the River Ebro is sufficient only to keep one outlet open. Four major phases of delta growth are recognized and some of these are known to have had more than one river outlet. The river has only recently changed to a new direction of discharge and abandoned a section of its channel. Levee, abandoned channel, marsh, lacustrine, beach/spit, lagoon, delta front platform and pro delta slope sedimentary environments are distinguished and described; sediment accumulation is most rapid on the delta front platform and the pro delta slope directly off the river mouth.

Seven living foraminiferal assemblages are described and a method, involving the use of 'percentage similarity indices', is utilized for the detection of offshore faunal boundaries. Standing crops of foraminiferids vary from 7 - 1628 individuals per unit sample and highest values are recorded at the top of the pro delta slope southeast of the southern spit. Higher standing crops in the summer, compared to the spring, are attributable to increasing reproduction rates as temperatures become warmer. Diversity increases away from the shore and the area of maximum diversity approximately coincides with the area of maximum standing crop. Relatively high diversity and low standing crop, in relation to values off the Mississippi delta, indicate that the River Ebro probably has little influence on the waters around its delta. Fertility in most environments is probably not significantly different from an adjacent area of non - deltaic coastline.

The ecology and distribution of the most abundant species are treated in detail and occurrences related to measured environmental factors, including, depth, temperature, salinity and substrate. A study of the dead foraminiferids revealed that populations are fairly similar to the living populations but post - mortem transport of empty tests, particularly of the smaller species, is very active over the delta front platform off the delta flanks. Examination of foraminiferal faunas in offshore cores also demonstrated that there is considerable transport of empty tests from shallow to deep water, and in one case, that transport of large units of sediment from the lagoon entrances to deeper water has taken place.

The origins of the Ebro delta fauna are traced. Many species originated on the western side of the Atlantic and have probably migrated eastwards by means of 'rafting'. Others are indigenous or cosmopolitan, but the largest proportion of Ebro delta species have 'North Atlantic' affinities. These species reached the Mediterranean when sea temperatures were lowered during Pleistocene glacial periods and they were able to migrate southwards along the European coastline from the British Isles area.

Features of the Ebro delta sedimentology and foraminiferal ecology that will help distinguish ancient deltaic deposits include the vertical and lateral sequence of the sediments and the complex interdigitation of 'subaerial' deposits such as marsh and lacustrine sediments, the overall geometry of the deposits, the relative diversity of the foraminiferal faunas, the percentage occurrence of the dominant species in a sample, and the distinct character of the deltaic marine assemblage.

INTRODUCTION

An interest in ecology and in foraminiferids led to the choice of a research topic combining the two subjects. It was considered that a quantitative study based upon equal surface area sediment samples would be most useful so that valid comparisons could be attempted between samples and with other areas. Ecological interpretation is based only on the living foraminiferal populations; ecological information from dead populations is unreliable since tests are frequently redistributed after death. However, post - mortem distributions are examined separately and compared with the living populations. It was also considered that a seasonal study would be valuable since it would take into account variations in abundance and distribution of the living foraminiferids at different times of year.

A deltaic area was chosen for study because it provides a wide range of marine and marginal marine environments within a relatively small area and presents an opportunity to examine the effects of variation of environmental factors on foraminiferal distribution and abundance. Selection of a suitable delta was influenced by many practical considerations, including finance and transport. The Ebro delta was finally chosen because of its proximity to the British Isles, its relatively small size, and because it was believed that little or no research had been attempted on it before.

Very little quantitative work has been carried out on foraminiferids outside the U.S.A. and there has been practically no work at all on living foraminiferids in the Mediterranean. Only three deltas have been studied for their foraminiferal populations, the Mississippi, the Rhône and the Orinoco, and with the last two only the dead populations were considered. No complete seasonal study of foraminiferids from a deltaic area has yet been published.

Following the selection of the Ebro delta as an area for study, a reconnaissance field trip was undertaken in the summer of 1966. This confirmed the suitability of the area, but the size and range of the only boats available for hire at San Carlos de la Rapita confined the study to the southern side of the delta. It was hoped to conduct winter, spring and summer sampling surveys following the reconnaissance survey, but financial considerations made it impossible to arrange a winter field trip. Spring and summer surveys, in April 1967 and August 1967 respectively, were successfully completed and to compensate for the lack of complete seasonal information a second summer field trip was undertaken to sample off the northern part of the delta. In addition, further fieldwork was carried out on the delta itself, but it must be stressed that although a rough sedimentary examination of the delta was undertaken, a full sedimentological study is outside the scope of this thesis.

The thesis is divided into two parts. Part I is a short section on the Ebro delta, dealing with its sedimentology and history of development. Part II is concerned with the distribution and ecology of the foraminiferids in the deltaic area and comprises the bulk of the thesis. Throughout the study comparisons are made with other deltas, particularly those of the Rhône and the Mississippi on which there has been a good deal of information published, including studies on foraminiferids.

As far as the author can ascertain, very little research has been carried out on the Ebro delta. Dobby (1936) presented a paper dealing largely with the human geography of the delta while Jonker (1952) conducted a pollen analysis on cores of peat taken from a marsh near San Carlos.

The delta is now extensively used for agricultural purposes. It has a relatively rich alluvial soil, which, together with the availablity of water from the river for irrigation, contrasts markedly with surrounding land areas which are generally dry with a thin stony soil. In the last century only a very small part of the delta was cultivated, most of its area was covered by natural marsh. The only crop grown at this time was salsola, a plant which was burnt and its ashes used in the manufacture of soap. At the beginning of this century, more and more of the marsh was drained for agriculture, and about the same time it was realized that rice could be easily grown because of the availability of water from the river all the year round. Numerous canals and irrigation and drainage channels were dug all over the delta and each field was surrounded by ditches carrying water so that, at the appropriate time of year, the rice could be flooded.

Dobby notes that by 1936 only 33½% of the delta was unproductive; 58% of the total delta area was used for rice production and 8½% for horticulture. Further reclaimation of marsh has been undertaken since then and the author estimates that only 15 - 20% of the delta is now unproductive. Rice is still the main crop but over - production in the last few years in Spain has forced many land - owners to consider new crops. In some respects the delta is not an easy one to study. The extent of agricultural development means that very little natural environment remains and the numerous man - made canals and channels have altered many natural water features.

CHAPTER 1

LOCATION AND SETTING OF THE EBRO DELTA

The Ebro delta is situated on the Mediterranean coast of Spain between the latitudes of 40° 48' N and 40° 33' N and longitudes of 0° 38' and 0° 56' E. It is approximately 150 km. south along the coast from Barcelona and is within the Golfo de San Jorge, which, farther to the south becomes the Golfo de Valencia. The continental shelf along this part of the coastline is much wider than to the north or the south; off Barcelona the width of the shelf is approximately 16 km., while off the delta it is about 61 km. This widening of the shelf is not due to the deposition of deltaic sediments as off the Mississippi delta, but due rather to the morphology of the gulfs. These have relatively shallow water over most of their area and there are even some islands within the Golfo de Valencia. (See figure 1.)

There are several small deltas along this part of the Spanish coast. Examples are the Llobregat at Barcelona, the Beros and the Tordera deltas, but none of these approaches the size of the Ebro delta or projects conspicuously from the coastline. All along the Catalan coastline there is a narrow, low - lying coastal strip backed by ranges of hills running parallel with the coast. The evolution of the coastline and the geological history of the Ebro region will be considered since they have a bearing on the present setting of the delta. Most of the information presented has been obtained from Geografia de Catalunya (1958).

During the Mesozoic, the present coastal area from just north

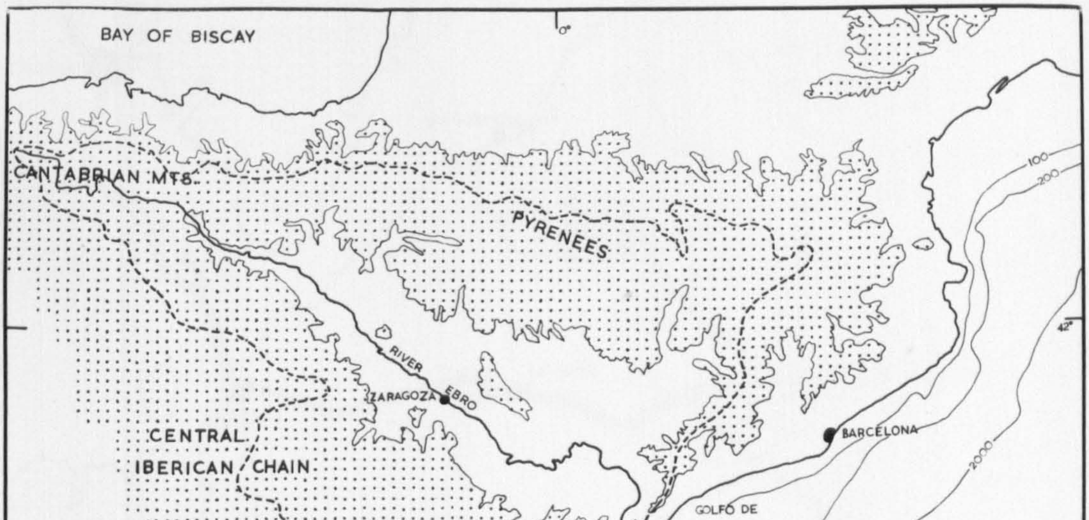


Fig. 1. Location of the Ebro delta.

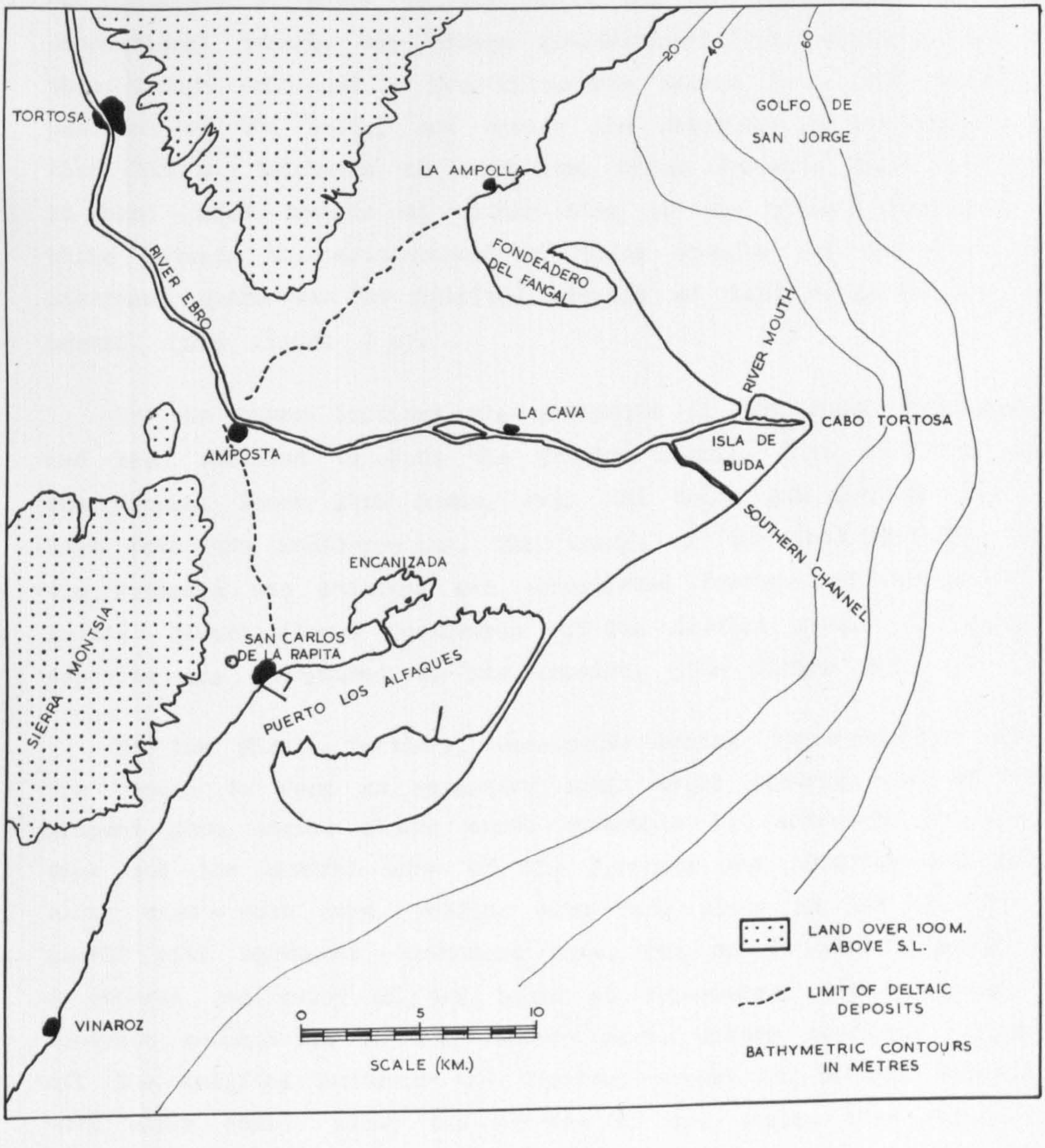


Fig. 1a. Local setting of the Ebro delta.

of Barcelona to south of the delta was the axial zone of a large depositional trough, the 'Fossa Mediterranea'. The deepest part of this trough commenced a few kilometres inland from the present position of the delta, and during the Mesozoic it accumulated more than 2000 m. thickness of sediments. Thick deposits also accumulated in east - west troughs on either side of the present Pyreneean axis, while between the southernmost of these troughs and the Fossa Mediterranea there was an uplifted stretch of land known as the Ebro massif. (See figure 2 a).

By the Lower Tertiary, the sediments of the Fossa Mediterranea had been elevated to form the Catalan massif. This stretched over the present lower Ebro Basin, over the delta and farther south and east into the Mediterranean. The trough on the southern side of the Pyrenees was enlarged and accumulated further thicknesses of sediments. Rivers flowed northwards off the Catalan massif and deltaic deposits are recognised at its margins. (See figure 2b).

In the Middle Tertiary, successive marine transgressions extended the trough to form an extensive basin which covered most of the present Ebro Basin. Alpine earth movements had commenced by this time and the central zone of the Pyrenees was uplifted and folded along east - west axes. Folding also took place in the Catalan massif with northeast - southwest axes. The uplift also resulted in a general shallowing of the basin of deposition, and evaporitic deposits accumulated in the eastern part. Rivers continued to run off the uplifted Mesozoic and Tertiary areas and deltaic deposits were again common along the margins of the basin. (See figure 2c). By the Upper Tertiary, the coastline was not a great deal different from the present day. The large basin had been elevated, and in the inland area there were a few areas of continental and lacustrine sedimentation. (See figure 2d).

Inland from the Ebro delta are ranges of hills running parallel

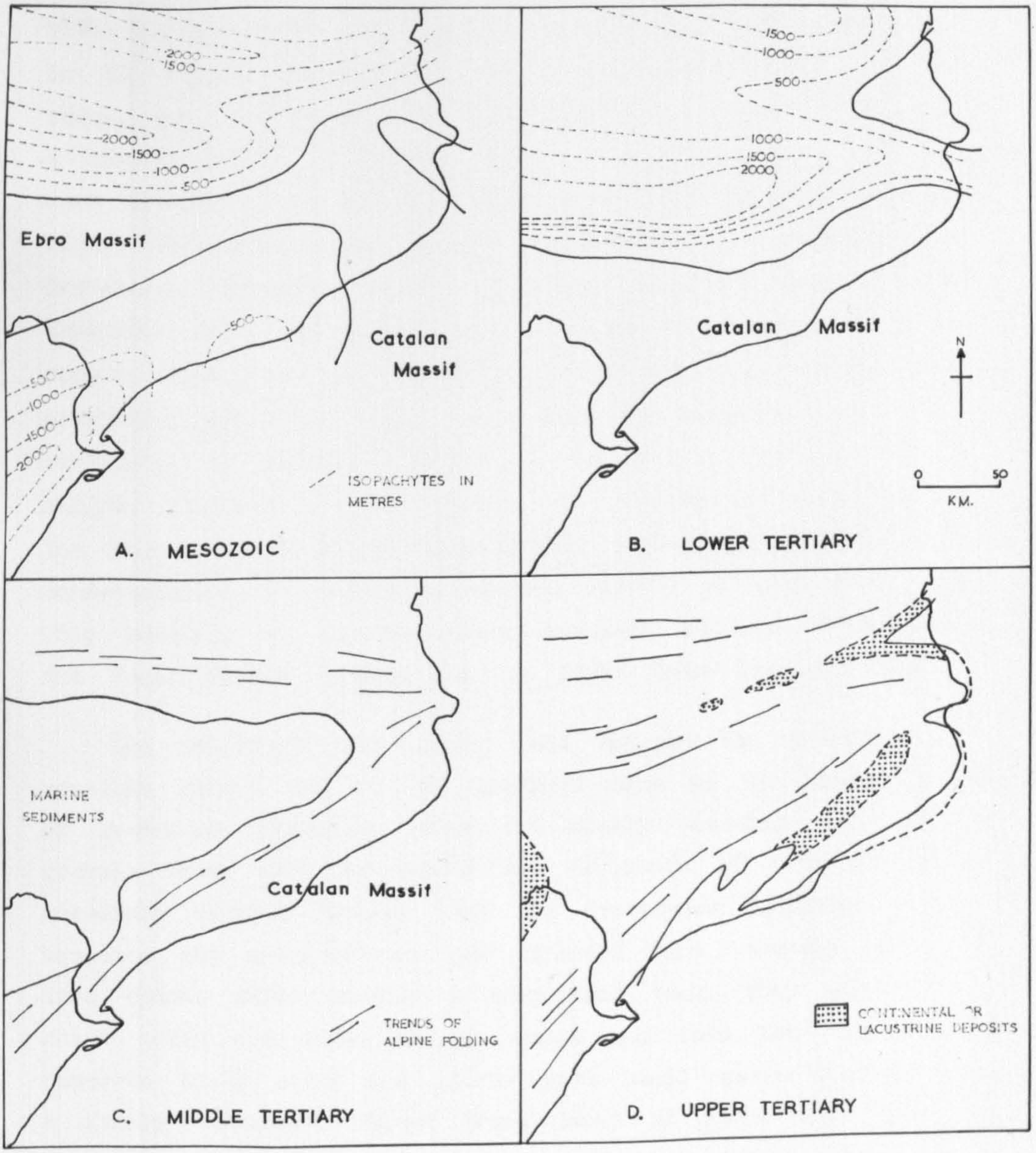


Fig. 2. Palaeogeography of the Ebro delta area during the Mesozoic and Tertiary. (Adapted from Geografía de Catalunya 1958.)

with the coastline and made up of the Mesozoic rocks accumulated in the 'Fossa Mediterranea'. South of the river is the Montsia range, set back about 1 - 2 km. from the coastline and rising to a maximum height of 768 m. North of the river a similar, although more extensive and higher, range runs northwards from Amposta. (See figure 1a). Both these ranges are composed of massively bedded Cretaceous limestones which are folded commonly about northeast - southwest axes. The limestones are grey in colour and Dobby (1936) reports that they are dolomitic in places. They contain a small proportion of broken shell material, but complete macrofossils are restricted to localized lenses up to 40 m. in length and 10 m. in height. Although a few specimens of oysters and corals were found, the fossiliferous lenses are almost exclusively made up of great concentrations of large gastropods, chiefly of the genus Ptycomphalus. Thin sections of the limestones revealed abundant foraminiferids in the fossiliferous lenses, but in other beds they are rare.

The relatively low - lying land between the coastline and the mountain ranges and on the landward side of the delta is composed of Quaternary deposits. These are mostly breccias, conglomerates and gravels whose main components are fragments of grey limestone almost certainly derived locally from the Cretaceous limestone hills. The breccias and conglomerates are cemented very strongly by a carbonate/ iron cement which creates a very hard rock. They outcrop on the coast north and south of the delta and form low 'cliffs' with numerous small coves and inlets with small sandy beaches. There is a fairly consistent raised beach level at about 2 m. above the present sea - level and another at an estimated 5 - 8 m. above sea - level. These levels have been commonly recognized along the length of the Catalan coast, and the higher one of the two is generally thought to have been formed during warm water conditions because of the presence of the sub - tropical mollusc, Strombus bubonius.

Along the non - deltaic part of the coastline, there are num-

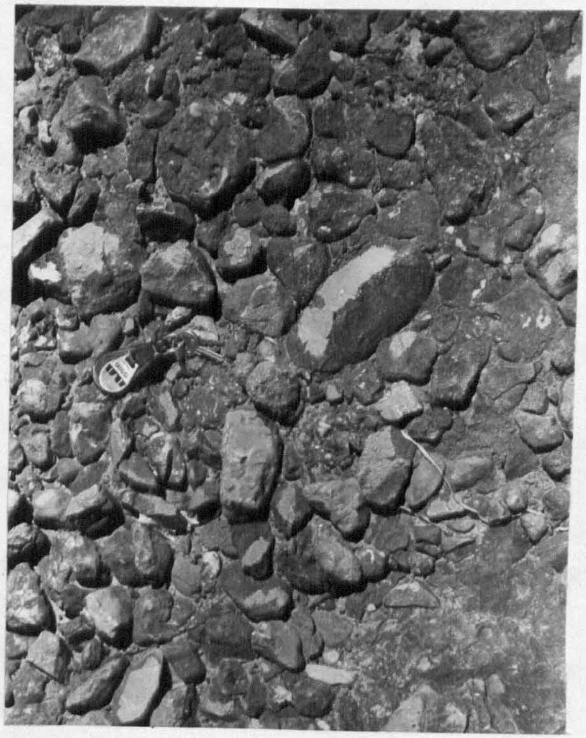


Figure 3: Typical Quaternary conglomerate

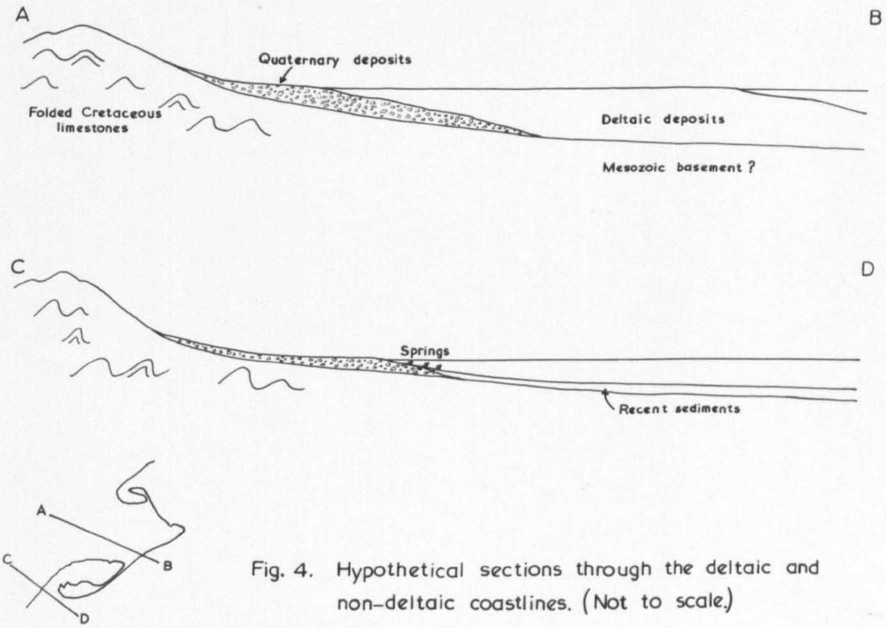


Fig. 4. Hypothetical sections through the deltaic and non-deltaic coastlines. (Not to scale.)

erous streams flowing into the sea off the high ground, but in summer these are invariably dried up and were observed to carry water only in times of heavy rainfall, as in prolonged summer thunder-storms. There are, however, a number of permanent springs that emerge at, or just offshore from, the coastline which carry cold freshwater from the mountains. In summer there is a strong temperature contrast between normal seawater and water from the springs, 26° compared with 18°. It seems likely that the water to feed these springs is conducted underground from the mountains within the Quaternary gravels. Dobby (1936) recorded that artesian water is found under part of the delta and when borings were made for the foundations of Amposta bridge, artesian water was met at a depth of 22 m. below the surface. It is possible that this water is carried within the Quaternary deposits which probably extend for a certain distance beneath the deltaic sediments. It is likely that the basement for most of the delta is made up of Mesozoic rocks similar to those outcropping in the coastal mountains. Hypothetical sections through the deltaic and non-deltaic coastlines are shown in figure 4 to illustrate the probable relationship between the different deposits.

CHAPTER 2

THE RIVER EBRO

The River Ebro is the longest river in Spain, having a length of approximately 600 kilometres. It originates in the Cantabrian Mountains close to the Atlantic coast of Spain and winds gradually southwestwards to discharge eventually into the Mediterranean. From its origin it flows into the extensive, flat Ebro Basin and then through more rugged land nearer the Mediterranean coast. The lower Ebro valley is frequently steep - sided and culminates in a relatively narrow 'gorge' near Tortosa from where the river emerges onto its delta. The Ebro has many tributaries and the total area of its drainage basin is approximately 64,000 sq. km. It drains three areas of high land as well as the Ebro Basin itself: the eastern end of the Cantabrian Mountains to the northwest, the southern side of the Pyrenees to the north and part of the Central Iberican Chain to the southwest. (See fig. 1.)

Across its delta the river varies in width from 150 - 400 m. Near the river mouth it is only 150 m. wide and one is struck by its narrowness considering the overall length of the river and the area of its drainage basin. Soundings printed on the Admiralty Charts of 1893 show the depth of the river to be extremely variable over the delta, ranging from 1¾ - 6¼ m. At the present mouth of the river it was observed that there was a considerable shoaling in a crescentic area extending from one side of the mouth to the other. It was not possible to approach this on the fishing boats for echo - soundings but the area clearly marked the line of the river mouth bar, and it was frequently further revealed by waves breaking over it. By observation of other areas on the delta, the maximum depth of water at which waves would break under normal weather conditions was approximately 2 m. Therefore, the depth of water over the river mouth bar is estimated to be of that order, and the 1893 Admiralty Charts show a depth of just less than 2 m. (1 fathom) for the bar across a previous river mouth. About 5 or 6 km. before its mouth the river bifurcates and a small distributary separates to flow to the southeast. This is a narrow stream with a maximum width of 60 m., but while old maps show water discharging from it into the sea, it is in fact now closed at its former outlet by a beach sand ridge.

The rate of discharge from the river has been estimated at 614 cu.m./sec. (data from Geografia de Catalunya, 1958). This is quite low compared to other rivers, e.g.

	Area of drainage basin (km^2)	Average discharge (cu.m./sec.)
Ebro	64,000	614
Rhône	95,000	1,620
Mississippi	3,184,640	16,500

It varies from month to month and the river regime for two stations, at Zaragoza and Tortosa, is shown in figure 5. Tortosa is only a few kilometres upstream from the delta and discharge there can be taken as virtually the same as from the river mouth. Maximum discharge occurs in the spring, from February to May, and although relatively high precipitation may contribute, the chief cause of high discharge is the spring melt of winter snows from the mountain areas within the catchment area. The summer period of minimum discharge from June to the beginning of August correlates with the period of lowest precipitation in the catchment area.

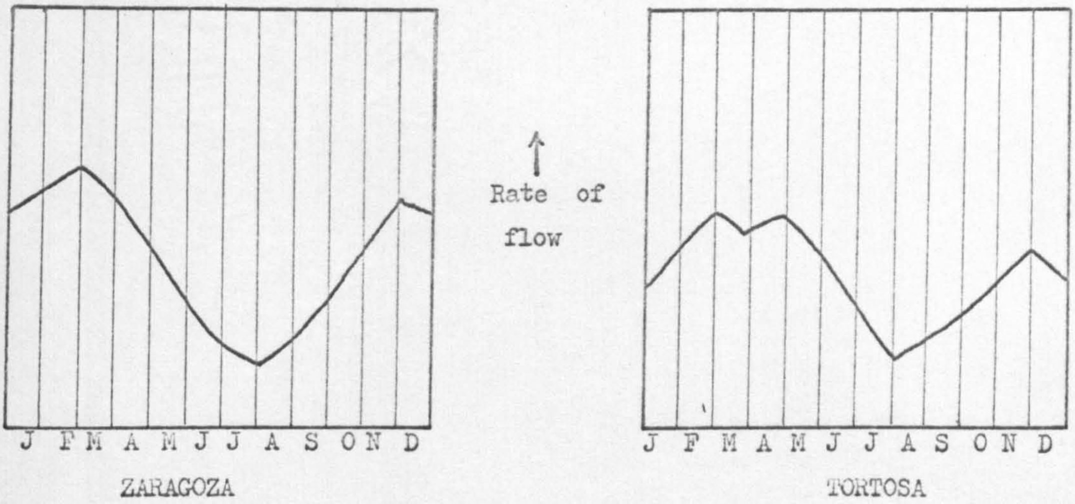


Figure 5: River regime at two stations.

Following this, discharge increases to a secondary peak in November as rainfall over the catchment area reaches its highest level during September and October. There is a slight decrease in discharge through December before the build up once more to the spring maximum.

The high level of water in the spring, particularly during March, frequently resulted in flooding over much of the delta. Now however, flooding is rarer because of the efficient canal and irrigation system which not only introduces water to the fields when required but also conducts away excess river water in times of exceptionally high flow. Under these conditions, there would not only be discharge of water into the sea from the river mouth but also from the many canals and drainage channels that empty into the lagoons. Exceptionally low water levels are also occasionally recorded, particularly during hot and dry summers. During an exceedingly hot period in August 1929, the discharge of water at Tortosa was estimated to be only 33.8 $m.^3/sec.$

The freshwater discharged by the river into the sea maintains itself as a distinct body of freshwater for some distance from the river mouth. The margins of the body are clearly visible, partly because of a colour contrast, the freshwater being a dirty grey and the sea water a 'Mediterranean' blue, and partly because of the 'foam line'. This is a thin line of foam and floating debris that marks the relatively sharp contact between the freshwater and normal seawater. During the spring survey, three surface water samples were taken on a run over the foam line with the middle sample on the line itself and with the two end samples about 10 m. apart. Salinity determinations for these samples produced the following results:

1. 38 $^{\circ}/oo$ (normal seawater) 2. 31 $^{\circ}/oo$ 3. 12 $^{\circ}/oo$ ('freshwater').

Bates (1953) noted the presence of foam lines off the distributaries of the Mississippi delta some distance from the shore and he presented evidence to support the theory that river flow should, because of the effect of Coriolis force, deflect to the right on leaving its mouth. Scruton and Moore (1953) also observed plumes of turbid water 'with sharp contacts with the seawater' up to 104 km. from the passes of the Mississippi delta. They suggested that the irregular nature of the plumes reflected pulses of flow from the river which could vary with variations in tides, currents and winds. It is not known how far from the mouth of the Ebro freshwater extends before it becomes totally mixed with the seawater, but foam lines were observed as far out as 6 km. during sediment sampling. Dobby (1936) reported that he had seen turbid water as far north as Atmella, a distance of approximately 20 km.

The orientation of the river discharge from the river mouth is approximately 010°, but at some times, particularly during low discharge, it appears that strong winds and wave action can deviate the main flow away from its normal line of discharge. Figure 6 shows the main body of freshwater flowing to the east and then around Cabo Tortosa and to the south. These conditions were never observed during any of the author's fieldwork, although on one windy day a foam line was seen directly off Cabo Tortosa.

Scruton and Moore (1953) stated that a foam line represents a line of convergence associated with the movement of one water mass over another. Water discharge from the mouth of the Ebro is typical hyperpycnal flow; i.e. freshwater flows over the seawater because of its lower density, and mixing takes place at the edges and underneath the freshwater body. All bottom water samples taken off the river mouth had normal salinity, and probably undiluted seawater extends as least as far as the river mouth bar. In periods of low discharge as in summer, seawater may progress some way up the river itself as a 'salt wedge'. The body of freshwater is probably not very thick; if the depth of water over the river mouth bar is of the order of 2 m., then this should represent the maximum thickness of the freshwater if it maintains itself as a discrete body. Scruton and Moore said that the freshwater 'wedges' off the passes of the Mississippi delta have maximum thickness near the pass mouths and thin to about ½ - 1 m. at their margins.

The turbidity of water off the river mouth is very high but it progressively decreases away from the river mouth as more and more sediment is released from suspension and deposited on the sea floor. Transparency of the water was measured at several sediment-sampling stations by noting when the sediment sampler (which was a silver colour) first became visible when being hauled to the surface and then measuring the remaining length of rope. This is not as efficient as the Secchi disc method but results can be tent-

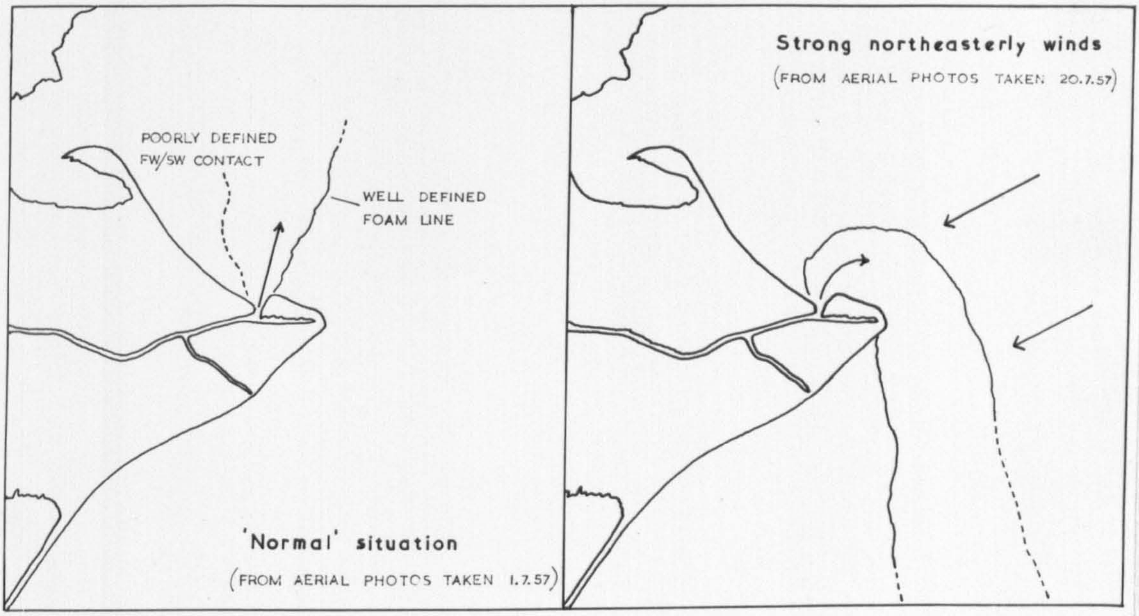


Fig. 6. Variation in the direction of freshwater discharge.

atively compared with those from off other deltas:

	Ebro delta (spring)		Rhône delta	Mississippi delta
	off southern delta flank	off river mouth	(average)	(low water)
3.3 km. from mouth	6m.	2m.	3m.	0.3m.
4.6 km. from mouth	9m.	4m.	5m.	0.6m.

(Rhône and Mississippi data from Van Straaten, 1959).

CHAPTER 3

MORPHOLOGY AND GROWTH OF THE EBRO DELTA

Morphology

The subaerial part of the Ebro delta has an area of 330 square kilometres, but this is only a fraction of the total area of deltaic sediments; subaqueous deltaic sediments are estimated to have an area of 307,200 sq. km. The subaerial delta is extremely flat, rarely rising to more than 1 or 2 m. above sea level, and the only prominent features on the delta are man - made, buildings, rows of trees etc. It has basically a simple deltoid shape with the base of the delta on the original coastline and the apex projecting into the sea. Behind the apex, two prominent flanking banks or spits protrude from the flanks of the delta to the north and south respectively.

The delta is asymmetric in so far as the area north of the river is smaller in area than the part to the south. The two spits also reflect this asymmetry: the northern one is smaller, being only 5 km. in length, while the southern spit is 15 km. in length. The two are also slightly different in shape: the southern spit has a long, thin bank of sand connecting the main body of the spit to the delta, while the northern spit widens gradually away from the delta flank. Both spits enclose shallow lagoons, the southern one being larger and slightly deeper, forming a natural harbour, Puerto Los Alfaques.

The frontal coastline of the delta is smooth and straight or gently curving, but the lagoonal coastlines are much more irregular with numerous drainage channels opening onto them from the main part of the delta. The western sides of the spits also have very irregular coastlines with low projections and shallow inlets all along their lengths.

The river mouth bar has already been discussed in chapter 2, but there is also a sandy bar just offshore along the whole length of the frontal delta coastline. This bar is usually within 30 - 60 m. of the coast and runs parallel to it. It probably represents the site of active transport of sandy sediments by longshore drift. Van Straaten (1959) reported similar 'longshore bars' along the whole coastline of the Rhône delta. He observed that there was sometimes a series of bars, up to 5 in number, which ran parallel to the coastline and which had their steeper sides facing the shore. Most of these bars were within the limit of wave action and although the deeper ones appeared to lie below this, they probably came within the wave base under storm conditions.

Profiles of the subaqueous part of the delta can be seen in figure 7. These were obtained from echotraverses run from the fishing boats (see chapter 6). The nearshore bar is not seen on these profiles because the boats were unable to approach that close to the shore. Profiles off the central part of both flanks of the delta (B and G) reveal the presence of a smooth - bottomed, shallow platform which slopes very gradually from nearshore to about 12 m. depth on the northern side, and about 18 m. on the southern side. Deeper than this the submarine slope steepens considerably. These platforms are also plainly evident in the bathymetry of the delta; figure 1a in chapter 1 illustrates how the 20 m. contour deviates considerably away from the coastline. The southern platform is the larger of the two.

The pro-delta slope is steepest off the present delta apex

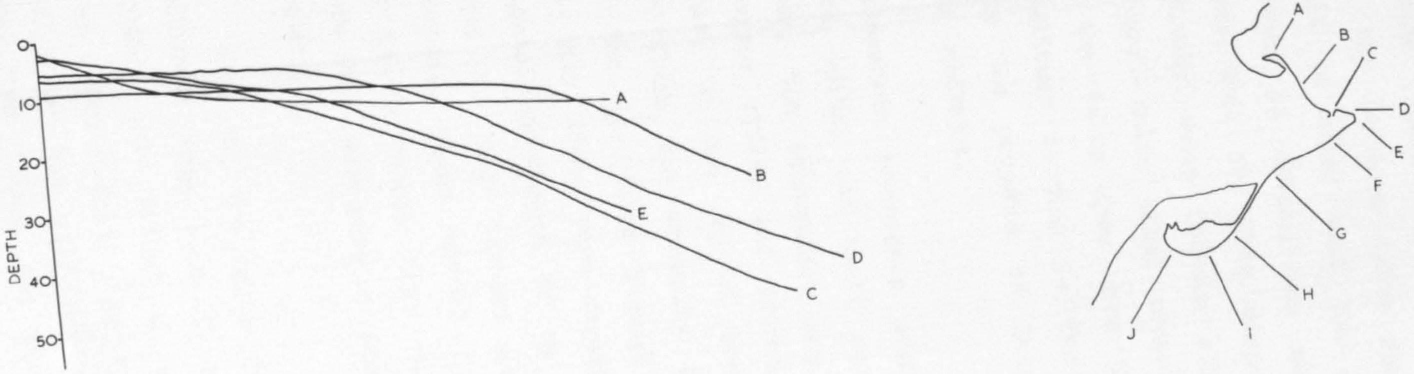
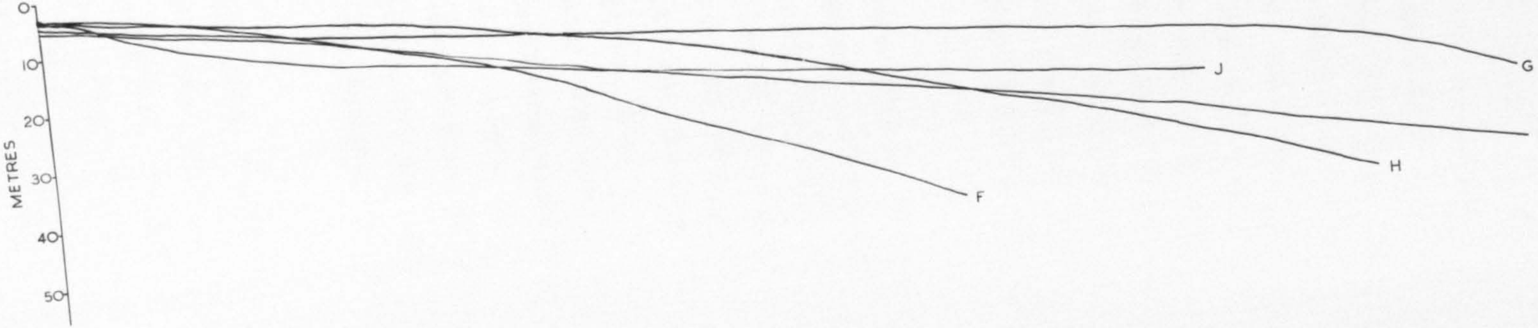


Fig. 7. Subaqueous delta profiles (from echo sounder records)



and also off the present river mouth although it appears in the latter case (profile C) that the river discharges first over the edge of the northern delta front platform before the slope steepens. It should be noted that the slopes of the profiles are much exaggerated; in nature, the steepest slopes are calculated to be just less than 1°. This compares with the Rhône delta which has a relatively steep deltaic slope of 2°, while the Mississippi has a pro - delta slope never greater than 1° (Shepard 1960). Profiles around the delta apex show that the sea floor, particularly in the shallower depths, is far from smooth. Its irregular nature may indicate the presence of large ripples or other surface structures in the sediment.

Elsewhere subaqueous profiles are remarkably smooth, especially off the spits, and small scale sea floor relief is apparently rare. However, the echosounder may not be sufficiently sensitive to pick out minor relief and probably only records larger structures. For example, on one day of boat - work the water off the southern delta flank was unusually transparent and it was possible to observe the sea floor through water depths up to 10 m. It was noticed that there were megaripples on the sandy sea floor with an estimated wavelength of up to 1 m. Their amplitude could not be gauged but they trended at approximately right angles from the coastline. Their overall extent and their significance is unknown, but it is likely that they cover large parts of the sea floor where the substrate is sandy. These were not detected by the echosounder.

Most of the major deltas of the world have shapes somewhat different from that of the Ebro and the latter does not fit readily into either of the accepted morphological classes of delta, the 'bird's foot' or 'lobate' types. Many other deltas are deltoid in shape but most are the opposite way round to the Ebro with the apex inland and the flat base of the triangle forming the deltaic coastline, e.g. the Nile delta. This is due to the development of a distributary system near to the mouth of the main river channel and subsequent sedimentary deposition around the network of distributaries. The Ebro at present has no distributaries, the flow from the river being insufficient to support more than one channel in the face of strong wave action from the sea. The Ebro delta probably has one of the simplest deltaic shapes possible, being formed by a single river channel opening into a body of water. Seaward forces have affected the final deltaic shape and Bates (1953) recorded that "In nature, the deltaic shape which finally develops depends on the magnitude of the non - equilibrium existing between the coastal forces of accretion and erosion operating near the outlet".

Zenkovitch (1966) also recognised that a simple deltaic shape could be produced by a single channel. He stated that "A typical and simple delta is formed by a single channel opening into deep water where wave action is strong enough to close completely one of the channels should it fork. In these conditions a river will construct a projection which will be increasingly attacked by waves the further it advances into the sea. Much of the sandy material will be shifted by the waves sideways from the mouth and incorporated into flanking banks. So far from halting the growth of the delta this will accelerate it. The Ebro delta in the Mediterranean is a close approximation to this idealized type".

Growth

As is the case with many other deltas, the growth of the Ebro delta has not been as straightforward as its basically simple shape might suggest. Its development has been complicated by a number of factors including changes in river flow and in sea level, together with erosion by the sea. Some deltas have been recognized as being formed of a number of imbricating deltas. Close examination of the Ebro delta revealed that the course of the river has not always been in its present position and four distinct phases of growth, or imbricating deltas, can be distinguished. It is possible that there may have been other growth phases which have left no trace. The four main phases are illustrated in figure 8 and can be listed as follows:

1. A primary phase at right angles to the old coastline.
2. A second phase to the northeast.
3. A third phase due east.
4. A fourth phase, recently initiated, to the north.

The first phase of growth that can be distinguished commenced with the river flowing farther to the south than it does at present. A perpendicular drawn from the point of emergence of the river from the original coastline probably represents the approximate course of the river during this stage. This line passes through the centre of the southern delta front platform and the latter is thought to represent the maximum eastward extent of the original delta apex. Aerial photographs taken in 1957 show an arrangment of fields on the southern side of the delta that marks out the original course of the river. Old charts (1893) support this hypothesis and even show water present in the old channel at that time. This initial phase probably involved fairly rapid growth in one direction, but later the river became diverted to a new course.

The causes of a shift to a new course are not fully understood but Scruton (1960) considered that a river would seek a new course if it became 'overlengthened'. This entails a river building out its deposits, as an elongate body, a relatively long distance into the sea so that the river has to flow a great distance to deposit its load. It may then seek a shorter route to the sea, probably by enlarging a breach in one of its levees some distance upriver from its mouth. Kolb and Van Lopik (1966) observed that

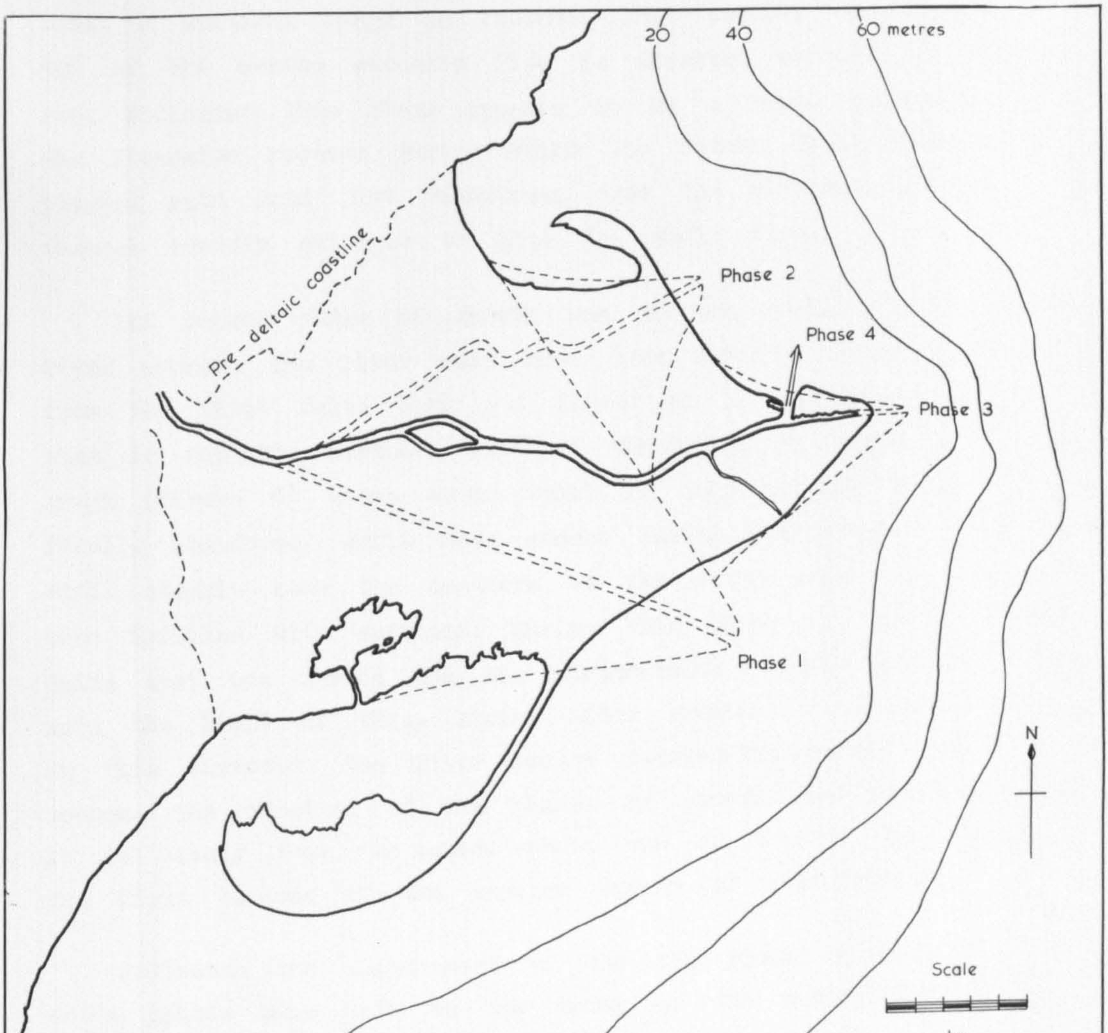


Fig. 8. Growth of the Ebro delta.

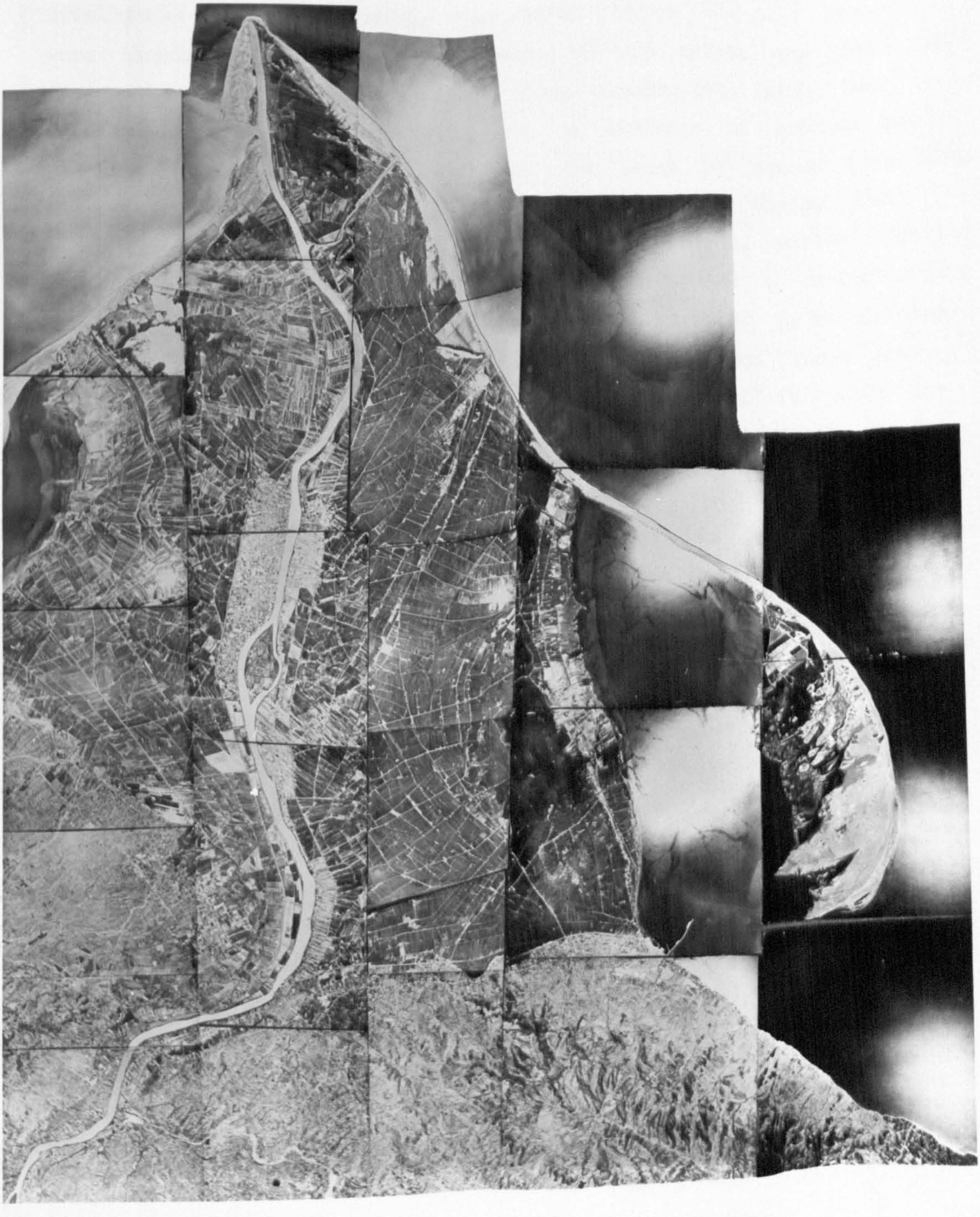
the abandonment of a Mississippi river course is a gradual process until a critical stage is reached. This usually occurs when 30 - 50% of the master stream's flow is diverted through the diversion arm. Following this there appears to be a rapid acceleration of the diversion process during which the former full - flow course is plugged with sand just downstream from the diversion and the new channel rapidly enlarges to take the whole flow.

The second phase of growth was to the north of the present river course. The river must have been diverted some distance back from the first delta apex and flowed in a meandering course over what is now the northern side of the delta. An older aerial photograph (figure 9) shows water still in this channel after it was finally abandoned, while more recent aerial photographs (figure 10) still clearly show the meanders of the river after the course had been infilled with sediment. During this phase of growth another delta apex was formed and the northern delta - front platform represents the limit of this. Again, after growth for a certain period in this direction the river became overlengthened and sought a new course. The duration of the phases of growth are not known, but it is likely that the second phase was of shorter duration than the first because of the smaller extent of its deposits.

Following the abandonment of the old river channels the two delta apices were left to the mercy of the waves. Their exposed position led wave action to be concentrated on them and erosion began very rapidly. The upper layers of sediment were eroded away and tranported mainly in lateral directions by longshore currents. Silt and clay fractions were probably removed in suspension and eventually deposited farther along the coast or in deeper water, while the sand fraction was incorporated into delta front beaches and into the two spits which grew as the old apices were worn away. In practice, erosion and reworking of sediment was probably going on whilst the delta was constructing these apices, and the

Figure 9: Aerial photograph of the Ebro delta (from Geographia de Catalunya, 1958), taken about 1930.

Figure 10: Mosaic of aerial photographs of the Ebro delta (obtained from the Servicio Geographico del Ejercito', Madrid), taken in July 1957.



development of the spits may have begun before the old channels were abandoned but full scale erosion of the apices and growth of the spits probably only commenced after abandonment. Along the present delta flanks there is plenty of evidence of erosion and retreat of the coastline. Erosion of the beach is common (see later, figure 13), and old marsh horizons are exposed in places just below the water on the northern side of the delta, another feature of a retreating coastline. Scruton (1960) said that a characteristic feature of the 'destructional' phase in his plan of delta development was the presence of numerous clean sand bodies. These are very common along the flanks of the Ebro delta and fit into the picture of a retreating coastline following the abandonment of the old apices.

The result of erosion of the old apices has been the establishment of shallow platforms off each of the delta flanks, i.e. an extension of the natural delta front platform. Van Straaten (1959) observed similar platforms off the Rhône delta, and he states "After these former courses became abandoned by the river, the upper parts of the deposits have been removed by wave erosion and a slightly inclined plateau was produced in each case. These plateaux are now covered by a layer of sand: a probably displaced residue from the sandy layers of the old foreset beds. The main part of this sand was probably moved shorewards by the waves and then carried sideways by longshore drift. The eroded mud has apparently been deposited in deeper water after having been carried about in suspension for shorter or longer periods".

The third phase of growth resulted in the formation of the present delta apex projecting towards the east. The river course during this phase was probably more or less the same as its modern course. The eventual abandonment of the eastern part of this course and the initiation of a fourth phase of growth to the north is clearer than previous diversions because it has taken place relatively recently. Various stages of the abandonment appear on maps and aerial photographs of different ages and it is considered worthwhile discussing the changes in detail.

The 1893 Admiralty charts show the river discharging due east, still in its third phase of construction. River flow at this time may have been temporarily higher than at present as the river was able to support a distributary, the southern channel. At this time the apex reached close to its maximum extent to the east. The first aerial photograph, of c. 1930, shows the initial stage of the diversion of the river to its new course. The river had apparently become overlengthened to the east and a breach occurred in the northern bank a few kilometres upstream from the mouth. At the time of the photograph, discharge through the breach was negligible. The southern channel was still active and it can be seen (figure 11) that its deposits resulted in a distinct bulge in the coastline along this part of the southern delta flank.

Although the Spanish map of 1942 indicates that there were several openings in the northern bank at this time, there is no field evidence to support this and the maps are probably inaccurate. However, the important point to be derived from this map is that flow through the breach was well advanced, although the old river mouth was still open and doubtless carrying a certain amount of discharge. The mouth eventually became closed by wave action plugging it with sand; the aerial photographs of 1957 show the new channel carrying the entire flow. The time taken for the change of course can be roughly calculated from the series of maps and photographs described. The breach of the levee probably occured around 1930 and by about 1945 the new course was taking the whole flow. This means that a period of the order of 15 years was sufficient for a change of course; the plugging of the old river mouth may have taken a further few years.

Since the abandonment of the eastern part of the river channel,

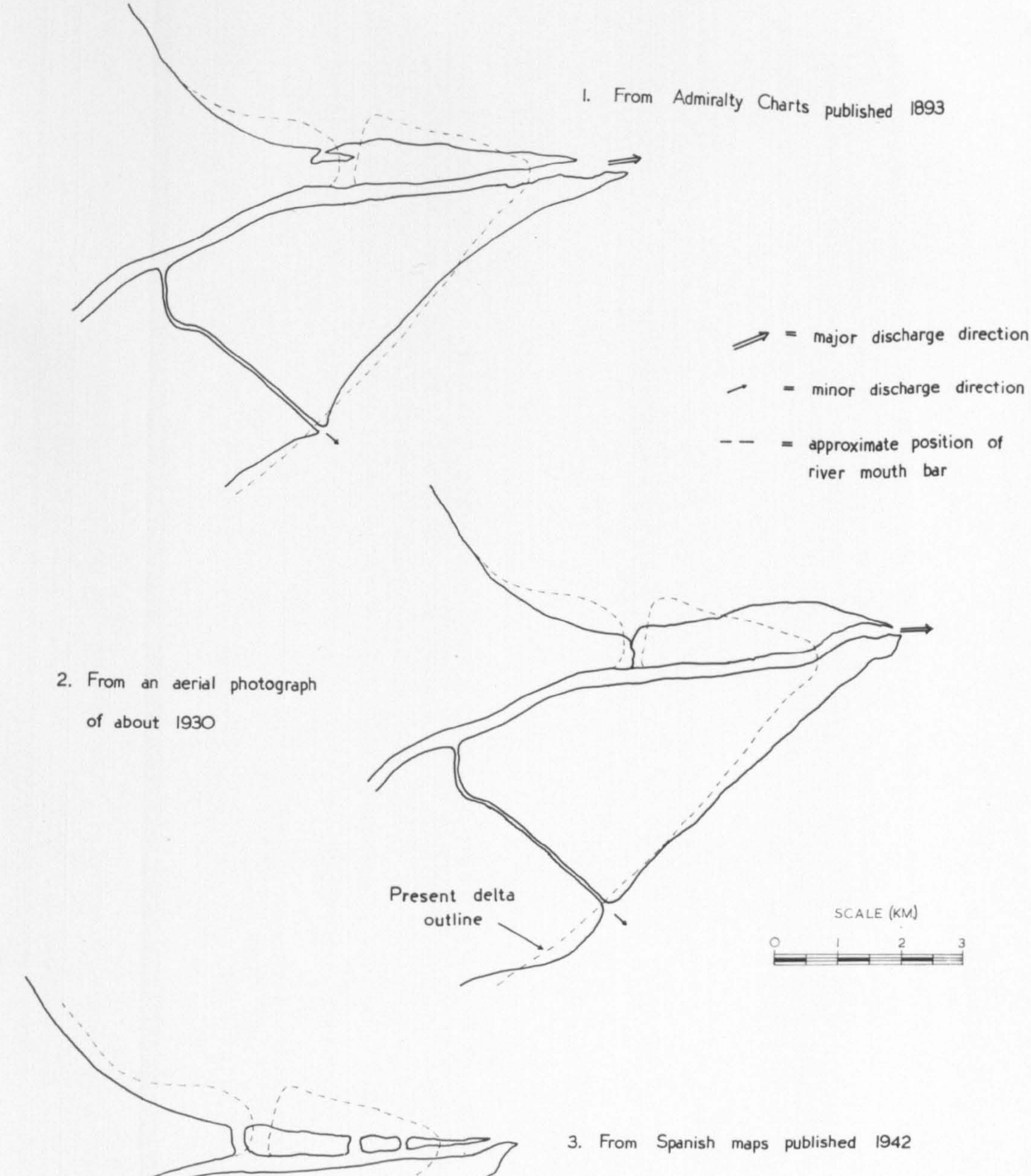
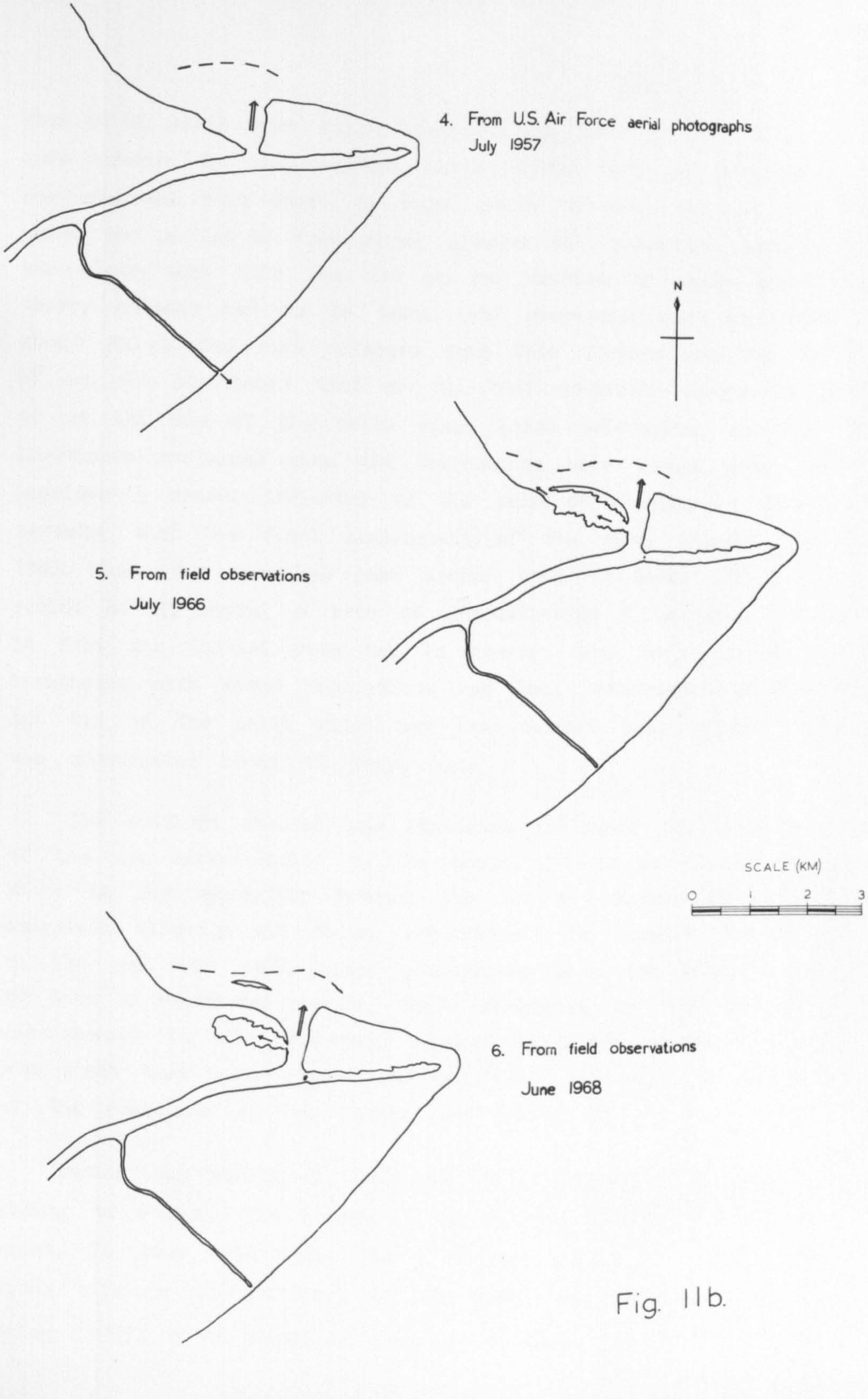


Fig. 11a (& 11b) Abandonment of the present delta apex.



4. From U.S. Air Force aerial photographs
July 1957

5. From field observations
July 1966

6. From field observations
June 1968

Fig. 11b.

the third delta apex (Cabo Tortosa) has been subject to considerable erosion by wave action. During field work at Cabo Tortosa it was observed that there is very active erosion; an area of turbid water up to 100 m. from shore extends all round the point. It was clear that this was due to the erosion of muddy sediments there, causing mud to be taken into suspension and transported away. About 200 m. due east offshore from Cabo Tortosa are the remains of an old lighthouse that on the 1893 Admiralty charts is positioned at the tip of the delta apex. Local information is that this lighthouse collapsed when the foundations were eroded away, and it provides a useful indicator of the rate of erosion at Cabo Tortosa. Assuming that the final abandonment of the river channel was about 1945, then the apex has been eroded back at least 200 m. in a period of 23 years, a rate of approximately 9 or 10 m. per year. In fact, the initial rate may be greater than this because a new lighthouse with stone foundations has been constructed at the present tip of the delta which may have slowed down erosion since it was constructed about 10 years ago.

The southern channel was abandoned following the establishment of the new river outlet to the north. It is not known whether there is any connection between the two or whether river flow had decreased slightly and become insufficient to support two outlets to the sea. The 1957 aerial photographs show the southern channel to have a restricted opening while fieldwork in 1967 revealed that the channel is now completely plugged by beach sands. The closure has meant that wave action has been able to work on the 'bulge' of the coastline at the outlet and smooth it slightly.

During the period of fieldwork from 1966 - 1968 it was interesting to observe the growth of the delta at the present river mouth. In June 1966 there was a barrier beach of fairly coarse sands offshore to the west of the river mouth, (see figure 11b). Bates (1953) noted that as soon as a river mouth bar forms, wave action is concentrated against it and it becomes the site for longshore sediment convergence. A barrier beach is then thrown up linking the bar to the coastline. The depression in between is known as a 'delta flank depression' and is bounded by natural levee, mainland and barrier beach. This appears to be the case off the present mouth of the Ebro, although the delta flank depression is relatively small and is a shallow 'lagoon'. In 1966, the western end of the barrier beach was about 200 m. from the shore and a small amount of river discharge was escaping through the opening, which was never more than 1 m. deep. Some muddy sediments were accumulating in the lagoon, but from the eastern end of the barrier beach it could be seen that the river levee was building up deposits and gradually blocking the entrance to the lagoon.

By July 1968, the barrier beach had joined to the coastline to the west and there had been considerable addition of sandy sediment to the frontal part. The western end of the lagoon had become virtually closed by levee deposits and there was only a small influx of water into it. Farther offshore another barrier beach was beginning to develop and the line of the river mouth bar had moved correspondingly farther out. The complete enclosure of the lagoon will make it a permanent feature on the delta and it may eventually become a shallow, brackish lake similar to those behind the beaches on the delta flanks. The latter may have been formed in the same manner. On the eastern side of the river mouth there was also a certain amount of growth, but marker poles positioned to measure the rate of growth were unfortunately removed by visitors.

Figure 12 illustrates the present state of the Ebro delta coastline. Apart from the river mouth area, the only other parts of the deltaic coastline that are advancing are the ends of the spits. Sands are transported along the delta flanks and eventually

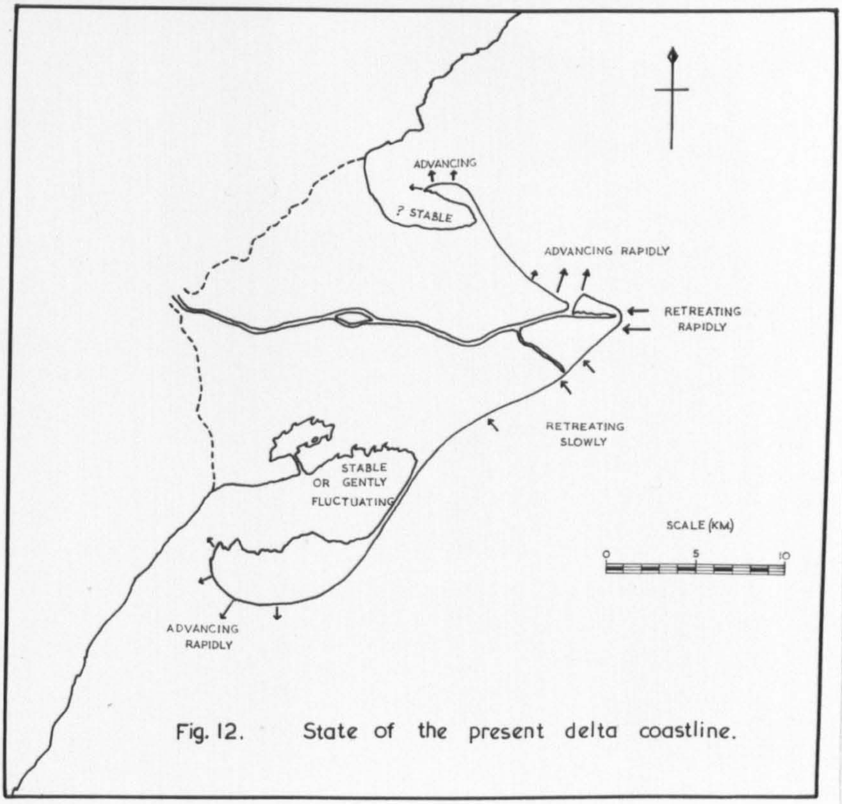


Fig. 12. State of the present delta coastline.

Figure 13: Beach erosion along the southern delta flank.

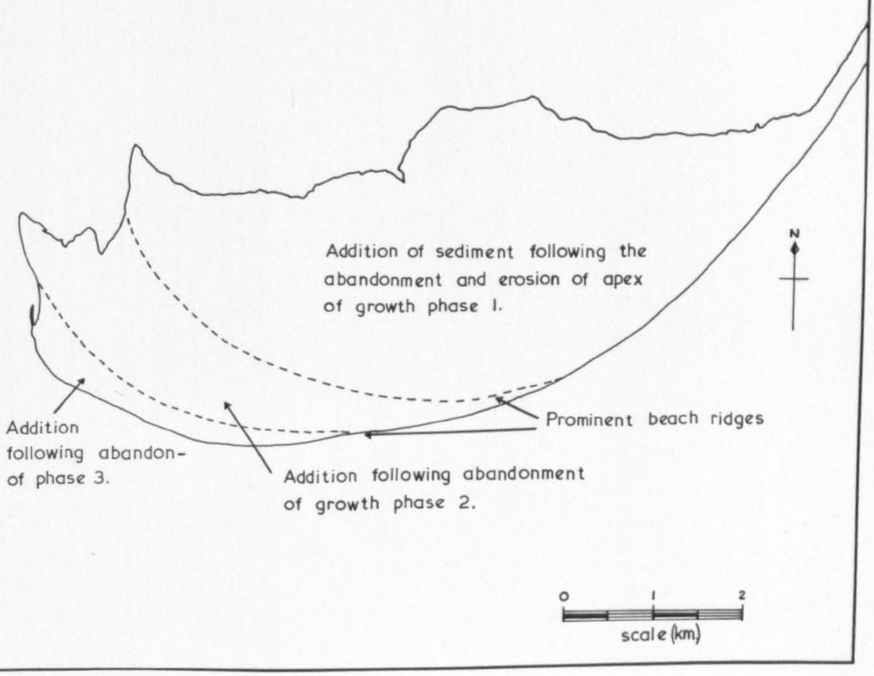
deposited in the quieter waters off the ends of the spits. Rapid erosion is taking place around Cabo Tortosa and there is probably also erosion operating along the delta flanks at a slower rate, (see figure 13). There is probably very little variation in the lagoonal coastlines although both erosional and prograding features were observed in places. However, overall rates of growth or erosion are probably very slow and the coastlines are only gently fluctuating.

The advancement of the southern spit to the south correlates very well with the growth phases and subsequent erosion of the delta. Three main phases of growth of the spit can be distinguished both in the field and on aerial photographs (see figure 14) by the distribution of prominent beach ridges. After each delta apex was abandoned they were very rapidly eroded and material was added correspondingly quickly to the southern spit. As an apex was progressively worn down, the rate of erosion, and consequently the rate of addition of material to the spit, slowed considerably. This allowed the development of a more permanent beach ridge on the southern end of the spit with a high dune line. Abandonment of the next apex resulted in increased rate of addition of sediment once more, rapid growth of the coastline with less opportunity for the development of a prominent beach ridge. Since the abandonment of the third delta apex in c. 1945, there has been growth of about 300 m. to the south up to 1957 (measured from the aerial photographs), a rate of approximately 30 m. per year.

Age of the delta

Unfortunately there is little evidence available for dating the origin of the Ebro delta. Jonker (1952) analysed pollen from peat samples taken near San Carlos and found that the peat was formed almost entirely in the Subatlantic period, less than 1000 years

Fig. 14. Growth of the southern spit. (From aerial photos 1957)



ago. The delta is underlain on its landward side by Quaternary gravels so its history probably does not extend beyond the Pleistocene. Other deltas along this part of the Mediterranean coastline appear to be of approximately the same age. Kruit (1955) observed that the Rhône delta was underlain by Pleistocene gravels, while Geografia de Catalunya (1958) states that the Llobregat and other deltas on the northeastern Spanish coast were initiated following the great Würm glaciation 25,000 years ago. It is possible that following the great glacial periods river flow was exceptionally high carrying melt - water away from the ice sheets and this may have provided the stimulus for initiation of deltas.

CHAPTER 4

SEDIMENTARY ENVIRONMENTS

Introduction

As has been previously stressed, a detailed sedimentary study has not been attempted, and the original purpose of examining the delta itself was to provide some background information to the foraminiferal studies. Field observations have been analysed to present a general picture of the sedimentology of the Ebro delta. Marine sediments were processed primarily for foraminiferids and grain size analyses were therefore not possible. (The methods of collection and processing of offshore sediment samples are fully described in chapter 6.)

Standard nomenclature for sediments has not been used since terms such as silt and clay require an accurate assessment of grain size. Size ranges for recognized sediment grades are as follows:

sands	(fine to coarse)	.063 - 2.0 mm.	(diameter of rounded
silts	(" " ")	.0039 - .063 mm.	particle)
clay	(" " ")	.0039 mm.	

In the field and during laboratory processing, sediment samples were wet sieved through a 200 mesh sieve. This has an aperture size of .076 mm. and so any residue on the sieve after sieving must come within the sand grade of sediment. For each sample the volume of the sieve residue was measured and related to the volume of the sediment before sieving and a figure derived to give the percentage of sediment with grain size greater than .076 mm. This size is close to the lower size limit of the sand grade of sediment and so the percentage figure can also be taken as indicative of the percentage of sand in the sediment sample. Sediment which passed through the sieve is referred to as 'mud' since no distinction can be made between silt and clay grades.

A rough classification for the marine sediments has been devised based on the percentage of sand grade material which they contain:

More than 80% sand = 'sand'
50% - 80% sand = 'muddy sand'
10% - 50% sand = 'sandy mud'
Less than 10% sand = 'mud'

Study of the subaerial part of the delta and examination of the submarine sediments showed that over the whole deltaic area a number of distinct sedimentary units could be distinguished. Shepard and Moore (1955) defined a sedimentary environment as a "Spatial unit in which external physical, chemical and biological influences affecting the development of a sediment are sufficiently constant to form a characteristic deposit", while Scruton (1960) said that sedimentary enivronments are defined by sediment sources, processes and their intensities, and rates of deposition. Allen (1965) noted that the nature of the detritus supplied to a sedimentary environment is essentially independent of the factors which operate over such a unit and is only determined by factors operating in adjacent environments, especially those upstream of the deltaic area.

Ebro delta sedimentary environments have been loosely divided into those on the subaerial part of the delta: natural levee, abandoned course, marsh and lacustrine, and those in the sea or of marine construction: beach/spit, lagoon, delta - front platform and pro - delta slope. The approximate areal distribution of these

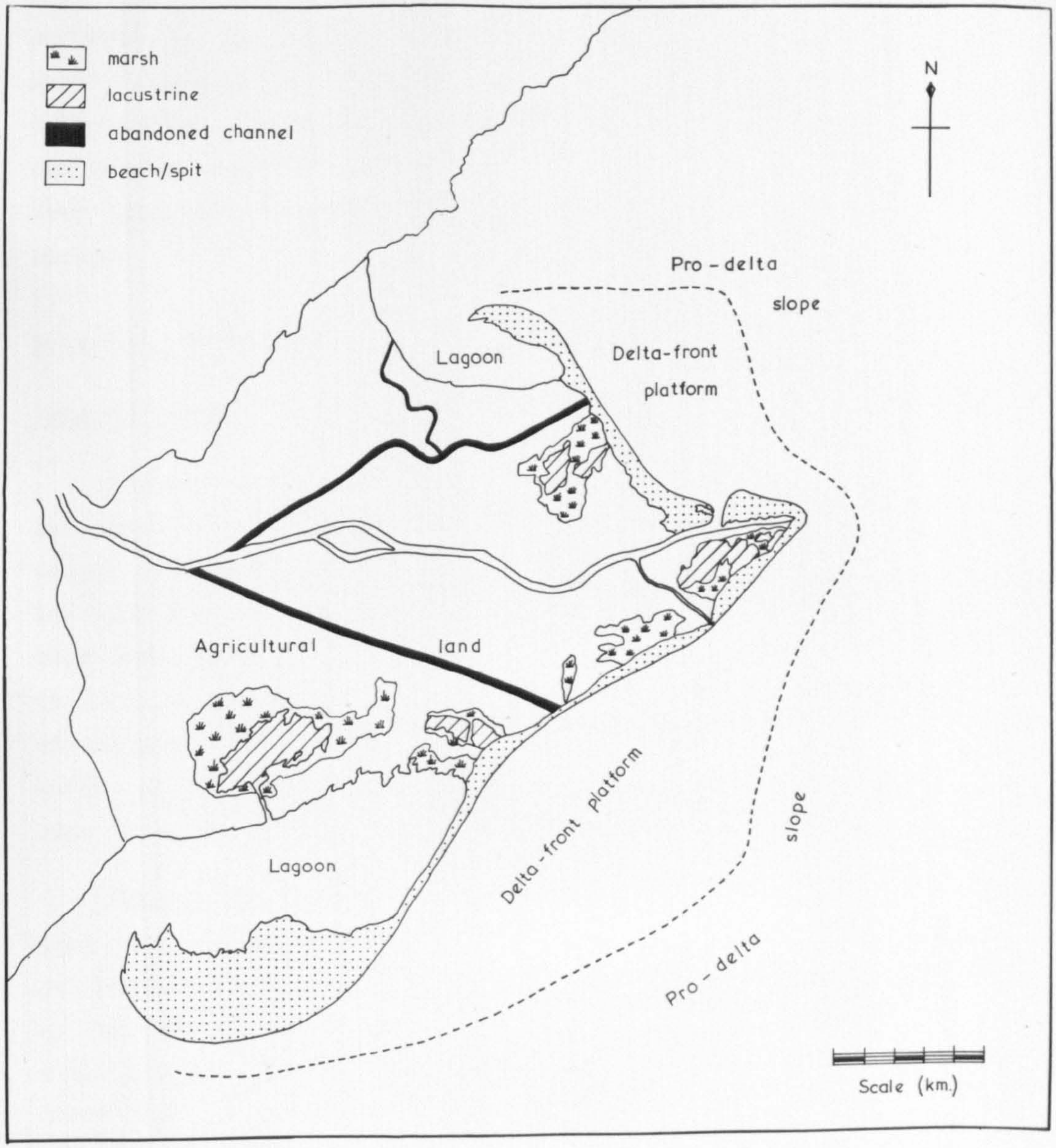


Fig. 15. Areal distribution of the sedimentary environments.

environments is shown in figure 15. In the classical sequence of delta deposits, the subaerial environments plus the beach/spit and delta - front environments would comprise the 'topset' beds while the pro - delta slope is equivalent to the 'foreset' beds. The 'bottomset' beds or offshore clays were not reached in the present survey.

Subaerial environments

Natural levee

Natural levees are the deposits on the sides of river channels and deposition generally only occurs when the river floods over its banks. They are usually elevated above the level of the surrounding deltaic land and on some deltas form the only conspicuous highs over the whole area. On the Ebro delta it proved very difficult to find a levee in its 'natural' state because they have been extensively built over or cultivated. In many places they have been built up to prevent the river eroding its banks and from flooding over them in times of high discharge.

Where they can be distinguished, the levees rise to an estimated 3 m. above the level of the river and extend laterally for at least 50 m. Kolb and Van Lopik (1966) found that levee deposits on the Mississippi delta vary in height above sea level from 2 - 8 m. and in overall thickness from 3 - 6 m. A section dug in the levee on the northern bank of the Ebro near to the river mouth revealed 1 m. of sandy muds before the water table was reached. The section revealed an occasional lamination of more muddy sediment and the sediments generally have a high organic content, particularly of small blackened pieces of woody material. Shepard (1960) reported that woody debris is common in the levees of the Mississippi delta.

Dobby (1936) also had difficulty finding a suitable levee to to examine and eventually described an eroded section opposite La Gracia (the island in the middle of the river half way across the delta). He recorded, "At the top, half a metre of loamy alluvium; beneath this, another half metre of peaty material, black with much woody vegetation not very advanced in decomposition. Below this again, another half metre of heavy clay whose deeply fissured black structure shows that it has been well dried out before succeeding clays were laid upon it. Salt crystals can be seen very prominently between the upper and peaty layers".

Abandoned river courses

After a river has shifted to a new course, the abandoned part of the old river course gradually becomes infilled with characteristic deposits. The Ebro delta has two such infilled abandoned courses and a third that is in the process of being filled which provides the opportunity to examine abandoned course sediments in situ and in the process of accumulating.

The distribution of abandoned course deposits is shown in figure 15. They are exposed at the surface in a small area behind the present beach on the northern abandoned course but elswhere they are hidden by superficial deposits that have been extensively worked for agriculture. Cores taken along the northern abandoned course revealed uniform deposits to a depth of at least 6 m. (see chapter 9). The deposits in the abandoned courses of delta growth phases 1 and 2 are typically grey - green unlaminated clays with the relatively high proportion of organic material that is characteristic of fluvial sediments.

The recently abandoned river channel of growth phase 3 gives an opportunity to study the accumulation of abandoned course deposits. At the point of diversion there is a line of coarse deposits built up by the river. At present, there is only a small amount of water passing over this 'wedge' and the water can be seen to be very turbid, carrying fine clays in suspension, (see figure 16). At the edges of the channel the clays were observed on the bottom and they appear identical in character with the deposits already described from the older infilled channels. The mouth of the channel is blocked by beach sands and there is also a considerable quantity of sand being contributed to the channel from aeolian sand dunes migrating over the area to the north, (see figure 17).

Kolb and Van Lopik (1966) recognised abandoned course deposits on the Mississippi delta and said of an abandoned course that, "For most of its length and for a considerable time after abandonment, the course is a fairly elongate body which gradually fills with the fine - grained sediment carried in by river flow. It may also be filled upstream by tidal currents carrying sands and silts".

Marsh

The marsh environment consists of waterlogged areas with a thick mat of vegetation (grasses, sedges, bullrushes, etc.). The vegetation is not, however, consistently thick; there are often smaller or larger areas of standing 'black' water dotted with grassy clumps. The water is invariably very shallow with abundant floating vegetation and algal 'scum', (see figure 18).

The marsh is a 'paludal' environment, i.e. characterized by highly organic sediments. Dying vegetation is contributed to the sediment and decay is slowly brought about by anaerobic bacteria which thrive in the stagnant conditions. A typical marsh sediment is black and peaty with organic humus and larger plant fragments in various stages of decay. In many cases there is a proportion of inorganic sediment, occasionally sandy, but more often muddy. This sediment is probably introduced to the marsh areas when the river is in flood and sediment - laden water flows in via the

Figure 16: Looking eastwards across river to recently abandoned part of river channel. (Cabo Tortosa lighthouse in background).

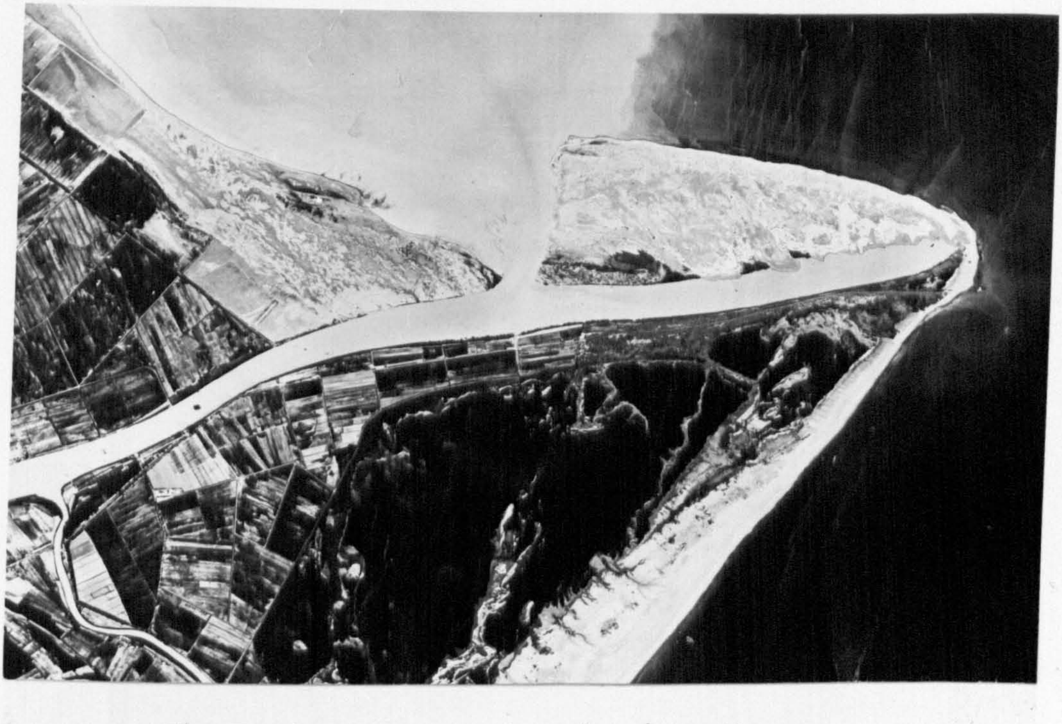


Fig. 17. Sand dunes migrating into the abandoned river channel.

Figure 18: Typical marsh scenery

numerous drainage channels and ditches surrounding the marsh areas.

Sections dug through marsh sediments show them to be mostly very thin, often less than 1 m. thick. In the marsh just south of Encanizada, a section revealed only $\frac{1}{2}$ m. of peaty sediments underlain by muddy sands with abundant shells of Cardium (typical lagoonal sediments). In addition, sections dug in present non - marshy areas have frequently revealed thin, peaty marsh horizons at various levels. Jonker (1952) took borings through a marsh 'near San Carlos' (probably just west of Encanizada) and found a total thickness of 2.3 m. of marsh sediments. Pollen analysis showed that the whole marsh was not older than the Subatlantic period, i.e. it had accumulated over a period of approximately 600 years.

It seems likely that marsh conditions are very rapidly fluctuating and that marsh deposits rarely accumulate for a great period of time in one place. When the delta was in its natural state, the marshes were probably frequently inundated by floods and may have been covered by a layer of sediment. Later, they would be re-established, but not necessarily in the same areas. In the past, marshes were undoubtedly more widespread than today, but now that man has colonized the delta they are rarely subject to flooding because of the good drainage system developed to protect the crops. In addition, much marsh has been reclaimed for agricultural land and if this process continues there will shortly be little natural marsh remaining.

The distribution of present marshes is shown in figure 15. The most extensive area is around Encanizada, and there are other areas behind the beaches on both the northern and southern sides of the delta. Swamp and marsh deposits are characteristic of most modern deltas in their natural states. Kolb and Van Lopik (1966) reported that more than 50% of the Mississippi delta is covered by marsh environments.

Lacustrine

Lakes are common on the delta near the shoreline but none occur far inland. They range in size from a few metres to several kilometres in width. Encanizada is the largest permanent lake and measures approximately 4 km. by 1 km., but other lakes, particularly the one on Isla de Buda, are almost as large. Figure 15 illustrates the areal distribution of the larger lakes and they have been divided into freshwater and brackish types.

Encanizada is the only freshwater lake, with a salinity of less than 3 °/oo. It has a narrow connection with the southern lagoon and is approximately 1½ m. deep at its deepest part. The bottom of the lake is covered almost entirely by thick, luxuriant growths of weed that grow almost to the surface of the water making it possible to negotiate the lake only in flat - bottomed rowing skiffs. The weed supports a very abundant fauna of gastropods, foraminiferids, ostracods etc., and there is a considerable fish population. The sediment has a high organic content derived from decaying weed and the decay is brought about by anaerobic bacteria, resulting in the sediment having a black colour. Only rarely is there a very thin lighter coloured surface oxidized layer. The inorganic portion of the sediment is mainly of 'mud' grade, although there is up to 60% sand near the connection with the lagoon. Sand content decreases away from the entrance of the lake and in the eastern part the sediment is almost completely muddy. The sandier sediments have the highest proportion of shelly material; near the entrance, this takes the form of whole and broken bivalve shells of the species that live abundantly in the southern lagoon. Shell content also decreases away from the entrance of the lake but farther east there is a preponderance of indigenous gastropods, ostracods and foraminiferids, and fewer bivalve remains.

The brackish lakes have salinities ranging from 8 - 37 °/oo and

Figure 19: Sand flat

Figure 20: Channels in sand flat area

are situated behind the beaches on the delta flanks. They are irregular in shape but in some cases quite extensive, with grassy islands around their edges. The immediate borders of the lakes are slightly elevated above the water level, with grass and scrub vegetation grading into marsh on the landward side. The lakes are rarely more than 1 m. deep and it is possible to wade through extensive areas of shoal water. The sediment varies considerably, being sandy towards the east and more muddy towards the landward side of the lakes. The higher mud content to the west is probably derived from sediment - laden water coming in from the river via the drainage canals while sands are probably derived largely from the beach and dune area from where it is transported landwards by wind action. Weed is more common on the muddy sediments but it never attains the luxuriant growth that occurs in Encanizada; sandy sediments sometimes support a sparse, grassy type of weed.

Between the sand dunes and the lakes there is often a wide expanse of sand - flat with occasional clumps of scrub vegetation, and it appears that in times of flood the lakes would extend to cover parts of these areas. There are several well defined channels extending into the sand - flat which probably conduct water during flood. Some had a little standing water in them at the times of examination and all are characterized by a sandy sediment with occasional small concentrations of broken shell material. (See figures 19 and 20).

Seawater must somehow reach the brackish lakes to account for their brackish nature. Either the sea breaches the beach ridges in times of exceptionally high tide, or else there is a continuous percolation of water through the beach sands. The origin of inland lakes is explained by Kolb and Van Lopik (1966) as the development of depressions in the marsh surface, and they add that their formation is normally a stage in the deterioration or partial burial of a marsh. This may well account for the origin of the Ebro lakes too, although a process was described earlier (see chapter 3) whereby a lake could be formed during the advancement of the coastline near the river outlet.

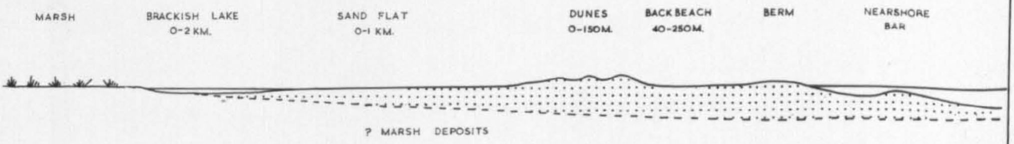
'Subaqueous' environments

Beach/spit

Delta front beaches are long and straight or gently curving, and a typical profile is shown in figure 21. The frontal part of the beach has a distinct berm grading into a flat back - beach, both composed of medium - grained, well sorted, wind - rippled sands. The total width of this part of the beach varies from about 40 - 250 m. Landward of the back - beach area is an expanse of low sand dunes, 10 - 150 m. wide and rarely rising to more than an estimated 2 m. or so above sea level. Sand dunes are best developed north of the recently abandoned river channel where they have grown to greater heights than on other parts of the delta. The dunes in some places are fixed by hardy vegetation and the sands are invariably wind - rippled. Over the whole beach and dune area there are many scattered shells that have been washed ashore, and frequently they become concentrated by wind action into 'shell pavements'. Behind the dunes there is either sand - flat grading into lake or marsh, or a direct gradation into marsh. Vegetation cover increases inland away from the dunes.

As has been stated in chapter 3, sand beaches are generally recognized as being characteristic of a retreating coastline associated with the abandonment of a deltaic system. Wave action is continually eroding the beach and pushing the coastline landwards and beach sands are blown by winds back over the marsh areas so that the beach effectively 'trangresses' over the marsh.

a) Typical delta front beach profile.



b) Representative section through the northern spit.

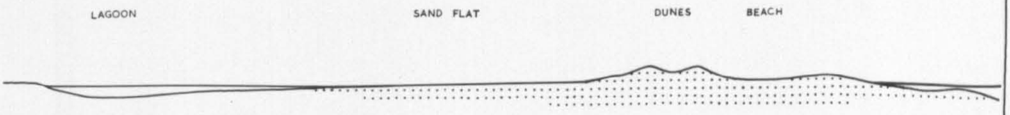


Fig. 21. Representative beach profiles. (Not to scale)

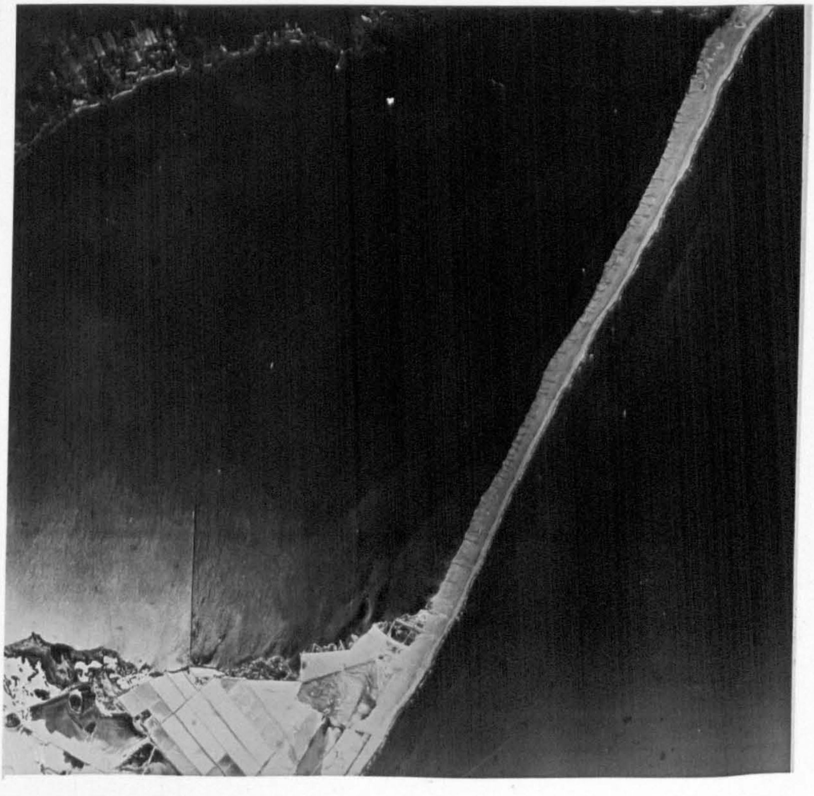


Fig. 22. Channels on the southern spit. (From an aerial photograph).

The spits have been included in the same environment as the beaches since they were both formed by virtually the same processes, are both composed of the same well sorted, fine to medium - grained sands, and because the two grade into one another. Also, the spits have typical beach profiles on their frontal sides and have dunes along most of their lengths. Dunes are best developed on the northern spit, but are very low or absent on the long thin bank linking the main part of the southern spit with the body of the delta. This thin connection varies in width from 250 - 500 m. and there are several breaks in the low dunes through which run well defined channels, (see figure 22). These are rippled and there are strand lines of debris along their sides indicating that at some time water must run through them. In heavy seas the beach berm may be breached and water flows through the channels into the lagoon while in times of high water in the lagoon they may conduct water from the lagoon to the back - beach area.

As the spits have grown, successive dune lines have merged to form central areas of low sand dunes with scrub vegetation. The sketch of the northern spit, figure 23, illustrates this. Behind the dunes there is an area of sand - flat which extends to the edge of the lagoon. The greater part of this is only fractionally above the water level and only a small rise in the water in the lagoon would inundate a large area. Retreating water from a previous period of high water has left behind a good deal of weed and algal scum, which, in places, has been dried by the sun to form a thin 'algal mat'.

The lagoonal coastline of the spits is much more irregular than the frontal coastline, with numerous inlets and low promontories. There is evidence that this coastline is continually fluctuating: sections dug about 100 m. inland from the lagoon revealed sandy sediments down to at least 1 m. with a few thin, irregularly spaced layers of mud. The latter are usually less than 1 cm. thick and

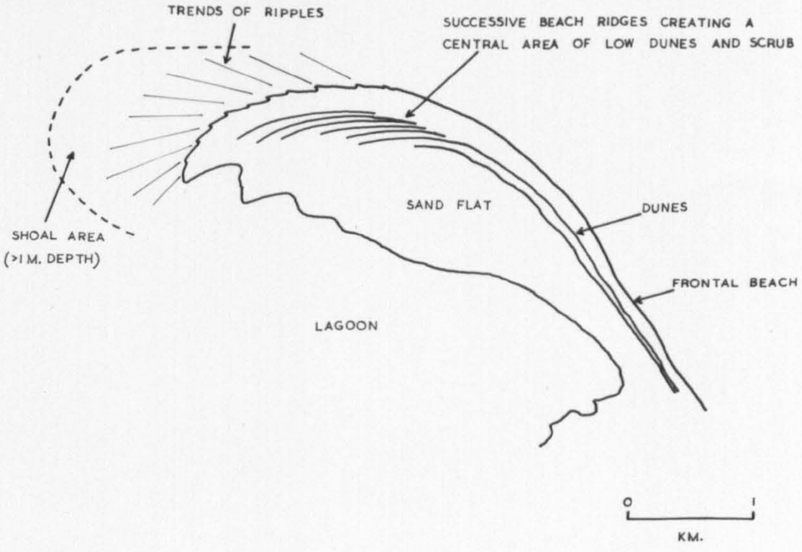


Fig. 23. Sketch of the northern spit.

probably correspond to the thin veneer of mud on the surface of the sands at the edges of the lagoon. A thicker band (5 cm.) of mud was encountered at about $\frac{1}{2}$ m. depth and a sample of this produced a typical lagoonal assemblage of foraminiferids. It is thought that these layers represent times when the lagoon extended farther east during higher sea level, and the thicker layer probably represents a more permanent extension during which true lagoonal sediments were deposited over this area.

The extreme end of the northern spit is somewhat different from the same area on the southern spit. Although both have a stretch of very shoal water with a rippled sandy bottom just off their ends, the northern spit has an irregular coastline with numerous small inlets. These become fewer and more angled to the coastline as the frontal part of the spit is approached, (see figure 23).

The barrier beach just off the river mouth has many characteristics in common with the beach and spit environments. Apart from the absence of a back - beach area, the frontal profile is the same as the delta front beaches. There is a line of very low dunes which are well covered by a variety of vegetation and behind this is a narrow stretch (up to 60 m.) of sand - flat with an algal mat in places. The sands, notably near the end of the beach close to the river outlet, are slightly coarser than those of the beaches.

Lagoon

Lagoon environments have been created on both sides of the delta by the growth of the spits. They have advanced to the north and the south and enclosed bodies of water with a restricted connection with the open sea. Both lagoons are very shoal near the spits and become deepest nearer the main part of the delta.

The southern lagoon is 6 m. deep in its deepest part while the northern lagoon is 4 m. Both have wide areas of their bottom covered by weed, particularly in the shoal water of their inner areas. The weed is frequently very dense and supports an abundant fauna including bivalves, (especially of the genus Cardium), gastropods, ostracods and foraminiferids.

The sediments vary in composition from clean sands in the shoal water adjacent to the spits to muds and muddy sands in the deeper parts. Generally, the amount of sand in the sediments decreases with depth and towards the lagoon entrances. The sediments have a relatively high carbonate content in the form of shelly material, especially in the inner corners of the lagoons. This is a reflection of the high level of animal activity and the low rate of sedimentation. The sediments also have a high organic content because of the continual addition of pieces of weed. There is rarely more than 1 cm. thickness of light coloured surface oxidized sediment; below this layer the sediments are black. This colouration is due to iron monosulphides such as hydrotroilite which are the product of the action of anaerobic bacteria on sulphates in the seawater and in the sediment. Other bacteria common in this reducing environment bring about decay of organic material with the production of hydrogen sulphide which gives these sediments a characteristic smell. The availability of oxygen in the overlying seawater will determine the level of the oxidation / reduction boundary. As the latter is very close to the sediment surface in the lagoons, it is concluded that water circulation (i.e. oxygen availability) is very poor. Other evidence bears this out, notably shell concentrations in the sediments. In these the shells are rarely broken up and accumulate close to the banks of weed on which the living animals flourish suggesting that current activity is almost non - existent.

Delta front platform

The delta front platform is situated immediately offshore from the delta flank beaches and shelves very gradually before grading into the pro - delta slope. The platform goes down to a depth of between 10 and 15 m. and varies in overall width from 1 - 8 km. It is widest off the central parts of the delta flanks where the old delta apices have been worn away. Typically, it is characteristic of deltaic advance, but on the Ebro delta the platform is being widened off the delta flanks as the coastline retreats under marine erosion.

It is a high energy sedimentary environment with strong littoral and longshore currents operating parallel to the coastline. Sediments are typically sandy but directly off the river mouth where the delta front platform is in a state of advance, the sediments are somewhat finer with muds, probably silt grade, as well as fine sands. Off the delta flanks the fine sands on the platform are derived either by lateral transport from the river mouth or by reworking of old delta deposits by current and wave action.

Pro - delta slope

Seaward of the delta front platform the subaqueous slope steepens to form the beginning of the pro - delta slope. Pro - delta deposits are the most widespread delta deposits as they form the greater part of the subaqueous delta. Their full extent off the Ebro delta is unknown since sampling traverses did not reach their seaward limits.

The deposits are almost entirely muddy in nature and there is a gradation from relatively coarser to finer sediments away from the shoreline. Deposits near the delta front platform are probably silts with a gradation through to fine clays in the offshore areas. The deposits are very homogeneous are there was no evidence of lamination in any of the deeper water sediment samples. The bulk of sediment brought down by the river probably accumulates on the pro - delta slope. Scruton (1960) said that the Mississippi brings down an average of 1 - 1½ million tons of sediment per day and of this 50% is clay grade, 48% silt and only 2% sand. Practically all the clay and silt accumulates on the pro - delta slope, forming in the region of 90% of the total sediment. Pro - delta deposits make up most of the thickness of a deltaic sequence of sediments and of an estimated maximum thickness of between 60 and 90 m. for Ebro delta sediments, probably more than three quarters of the thickness is made up of pro - delta silts and clays.

Relative rates of deposition

Sedimentation is undoubtedly most rapid directly off the river mouth where the body of seawater causes the outflow of river water to be gardually slowed so that its ability to carry sediment in suspension is gradually reduced. The river's bed load is largely deposited on the river mouth bar and this becomes a prominent site for attack by waves which results in the movement of sands laterally. Longshore transport of sediment is very active along the delta flanks and there is rapid deposition of sands at the ends of the spits.

Deposition on other parts of the delta slope is gradual unless a plume of turbid water from the river mouth is deviated over another area. This would result in a temporary increase in the rate of sedimentation in that area. Lagoonal sedimentation is generally very slow with only a small influx of sediment either via the lagoon entrances or to a lesser extent via the drainage channels opening onto the lagoons from the subaerial part of the delta. In the 'subaerial' environments, sedimentation is again very slow, but there may be sudden increases if any of the environments are flooded by sediment - laden water from the river.

Sedimentation rates are not constant throughout the year, and figure 24 shows that the distribution of sediments is slightly different from spring to summer. In the spring, river flow is at its maximum and is able to carry far more sediment. This in turn means a higher rate of sedimentation at this time of year and figure 24 shows that muddy sediments are widely distributed even over the southern delta - front platform, although the outer edge of the platform is characterized by an elongate area of clean sand.

In the summer, river flow, and hence sedimentation, is considerably reduced. With less sediment being deposited, the sediments laid down in the spring are subject to reworking by longshore and littoral currents. This is particularly marked on the southern delta front platform where the finer material deposited in the spring is winnowed away leaving a much wider area of clean sand. Part of the reworked mud is transported around the southern spit and deposited in the lagoon; it can be seen that there is more muddy sediment in the central part of the southern lagoon in the summer.

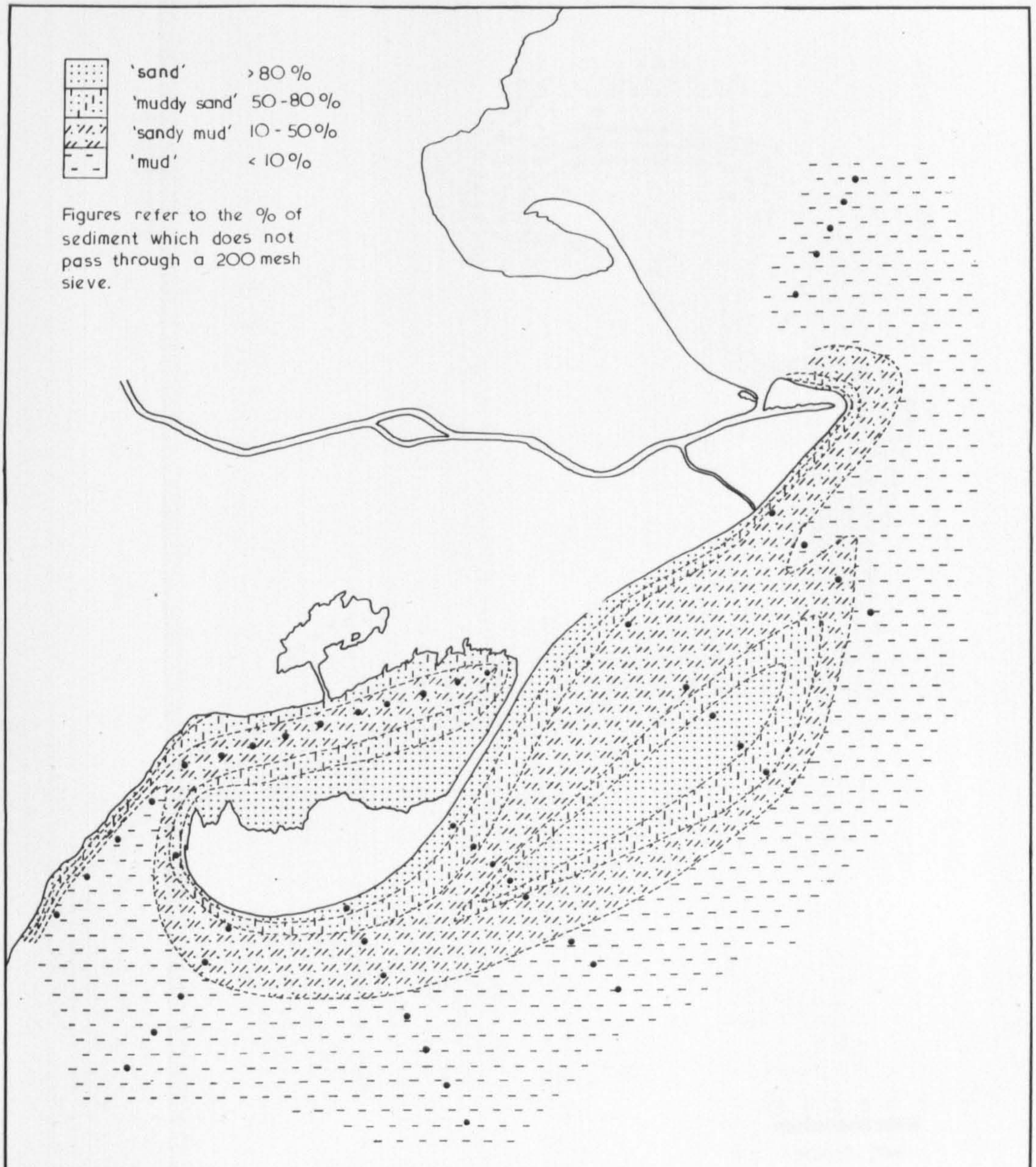


Fig. 24. Seasonal distribution of offshore sediments. a) SPRING.

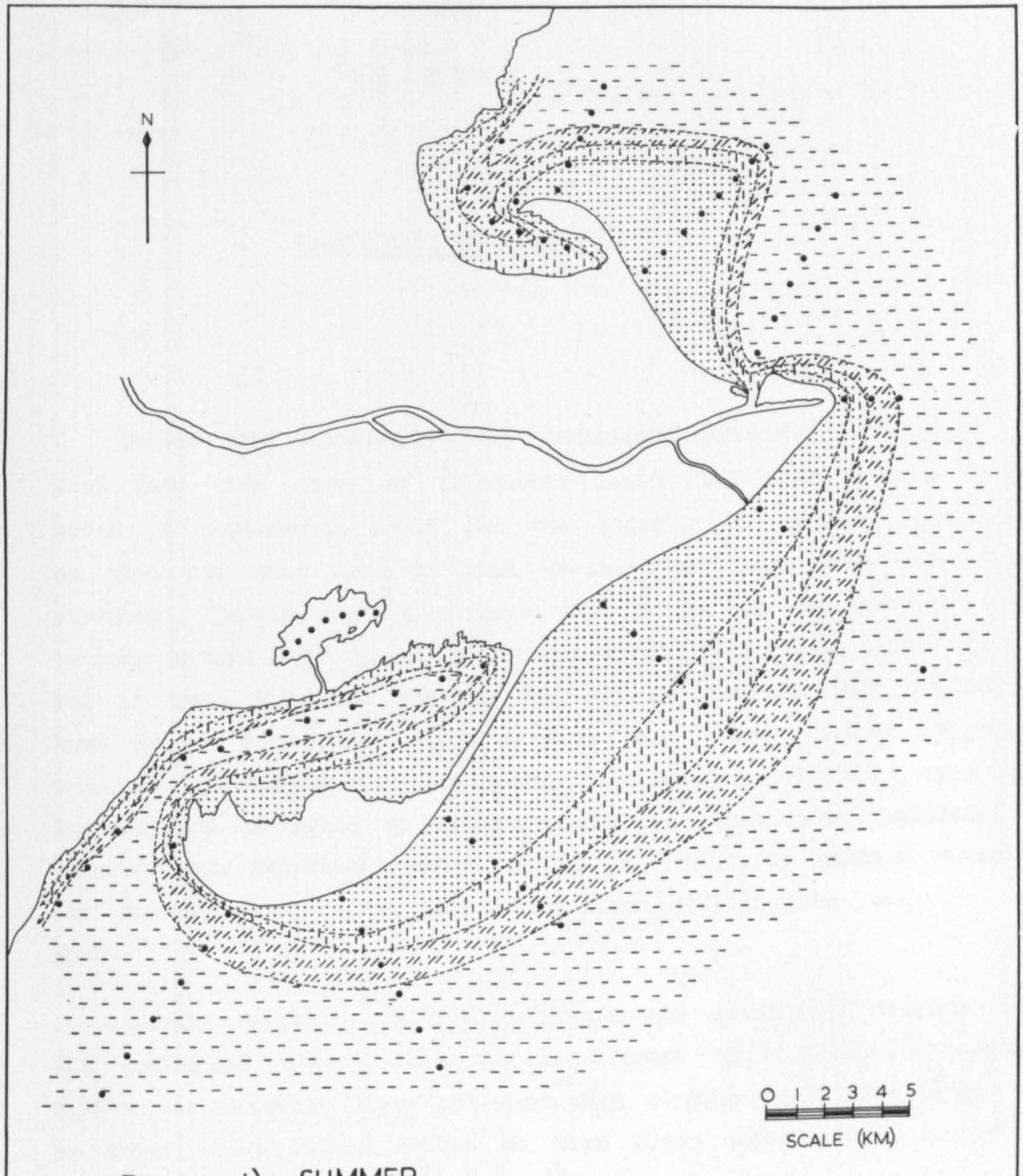


Fig. 24. b) SUMMER

CHAPTER 5

GEOLOGICAL IMPLICATIONS

Deltas are undoubtedly very important sedimentary features. They form wide areas of relatively rapid sedimentation over large areas of continental shelf and the quantity of sediment accumulated by them per unit area is much greater than any other marine environment. Deltas must also have been active in the geologic past because rivers were presumably running off land areas into the sea in much the same way as they do at present. Some workers have argued that delta deposits were less common because land areas were less extensive in past geological periods and there were no long rivers to build up deltaic sediments. This seems unlikely because even relatively short rivers can build up deltaic deposits, for example those along the northeastern Mediterranean coast of Spain.

Broadly speaking, deltaic sediments are relatively uncommon in the geological column. This may be because of a failure by geologists to recognize them and obviously a good deal more needs to be known about modern deltas so that older deposits can be more readily identified. The study of modern deltas has certainly gained momentum over the past few years and the discovery that they frequently provide suitable reservoirs for the accumulation of oil and natural gas has been an added stimulus.

It is necessary when studying a modern delta to attempt to draw sedimentological conclusions that will help in distinguishing ancient deltas. The amount of sedimentary information derived from the Ebro delta is limited; some long cores would have provided more useful geological information. Nevertheless, some general conclusions can be drawn.

It must firstly be stressed that modern deltas are seldom as simple in construction as they frequently appear. They are usually made up of several phases of growth, or imbricating deltas, superimposed upon one another. Partial or total erosion of older phases may occur concurrently with the construction of a new phase. All this tends to complicate the sequence of sediments in the delta in addition to the already complex relationships between the different sedimentary units such as marsh, lacustrine and beach deposits. These are likely to be complexly interdigitated; the Ebro marshes were shown to be very rapidly fluctuating features.

Theoretically there is a vertical sequence of deltaic sediments (figure 25) that it may be possible to recognize in older deposits. However, erosion and fluctuation of environments would mean that the ideal sequence is rarely attained.

The geometry of the delta deposits may present some useful information to help detect old deltas provided that sufficient three - dimensional information is available. Figure 26 illustrates that the thickest part of a delta is in the proximal pro delta region. Again, this may be complicated by erosion and imbrication but a relatively thick pile of silts and clays may indicate the equivalent area. Construction of isopachyte maps would be very useful for interpretation of older deposits. The latter should thin in all directions away from the thickest accumulation of sediments. On the landward side and beneath the deltaic deposits

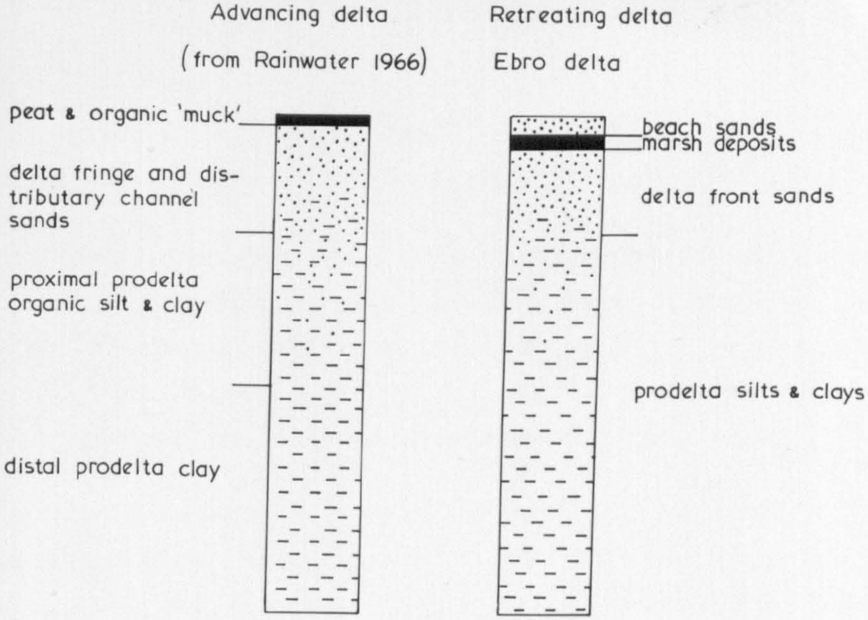
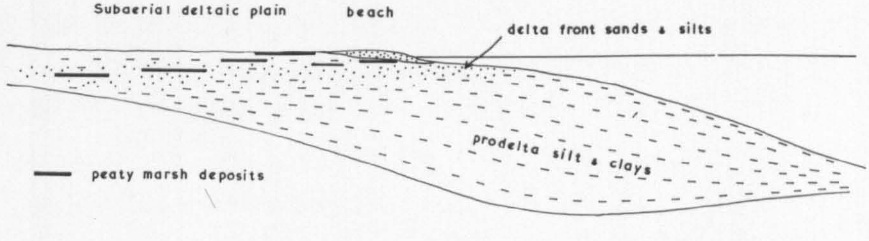


Fig. 25. Theoretical vertical sequences of deltaic sediments.

a) Parallel to the direction of delta progradation



b) Right angles to direction of progradation

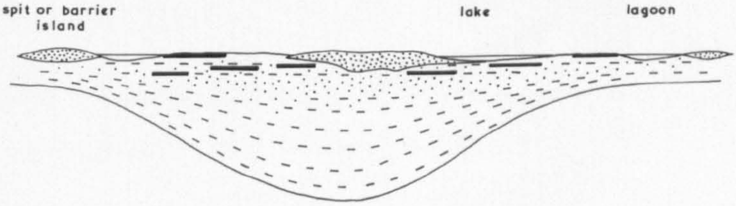


Fig. 26. Schematic sections through a deltaic mass of sediments

(Adapted from Rainwater 1966)

there will be older 'basement' rocks, and farther still on the landward side there may be aeolian, alluvial or continental deposits.

Many workers have been under the misapprehension that dip discordances will distinguish 'topset' from 'foreset' beds. This is very unlikely to be the case; the steepest part of the pro delta slope is only of the order of 1° and dip measurements are rarely sufficiently accurate to pick up differences of this magnitude.

The sediments themselves may be of use in recognizing ancient deltaic deposits. There will usually be a large thickness of silts and clays representing the pro delta deposits grading laterally into frequently fluctuating silts, sands, peats etc. representing the marginal marine and subaerial environments. Elongate sand bodies may indicate an old coastline; these would be equivalent to bar, delta front platform, beach or spit environments. All deltaic deposits, especially marsh deposits, have a relatively high organic content because of the quantity of plant and other debris brought down by the river. However, this feature will only be of use in interpretation of post - Devonian rocks; land plants did not appear until the Devonian. Ebro delta sediments show a general decrease in the percentage of sand grade material away from the coastline. It may be possible to recognize similar trends in older deposits. Shepard (1960) also noted significant trends in the median diameter values of sediments around the Mississippi delta.

In conclusion it can be stated that, provided there is an adequate sample coverage, it should be possible to recognize deltaic deposits by some of the sedimentary features discussed above. Rainwater (1966) summarized five categories by which deltaic deposits can be distinguished:

1. The geometry of the deposits.
2. The vertical and lateral sequence of sediments and environments.

3. Faunas.
4. The abundance of land plant remains.
5. Alternations (small scale) with shallow water marine and transitional sediments.

The significance of faunas in the interpretation of delta deposits will be discussed in chapter 11.

PART II

FORAMINIFERIDS

CHAPTER 6

METHODS OF COLLECTION AND STUDY

In all, four field trips to the Ebro delta were undertaken. A reconnaissance survey in June/July 1966 was followed by three main sampling surveys: April 1967, August 1967 and July 1968. 73 offshore sediment samples were collected in the reconnaissance survey by means of a small Van Veen grab, while a total of 124 samples (April 1967 - 46, summer 1967 - 50, summer 1968 - 28) were collected in the remaining surveys using a more refined sediment sampler. The subaerial parts of the delta were also examined and several sediment samples collected from the various environments. All the samples were transported back to Bristol for processing and examination of the living and dead foraminiferids contained within them.

Fieldwork

Boat

San Carlos de la Rapita is the largest fishing port for some distance along this part of the Spanish coastline and harbours a considerable fishing fleet. Most of the vessels are fairly small and only venture from the port in early morning, returning in the late afternoon. Financial considerations meant that only a smaller boat could be hired and the 'Jose Pedro' was chosen. It is a boat of approximately 10 m. length and, like most Spanish fishing vessels, was built to weather almost any seas. However, the design gives it a buoyancy that renders it a very unstable platform from which to carry out scientific work. The boat carried a winch which proved invaluable for raising the sediment sampler from the sea floor (figure 27) but otherwise had no equipment that was of use. Apart from the unbearable noise from the engine, the boat had the additional disadvantage of being very slow; for instance, it took 3½ hours to travel from San Carlos to Cabo Tortosa which severely limited the time that could be spent sampling during a day's trip to that area.

Unfortunately, only very small boats were available from Ampolla which were even less suited to sampling work because of their size and slower speed, and because none carried a winch. However, it was necessary to hire one of these vessels for the summer 1968 survey off the northern part of the delta and the sampler was manipulated by hand. The only boat suitable for sampling in Encanizada was a flat - bottomed rowing skiff, and one was duly hired and the sampler again manipulated by hand.

Sediment sampling

It is desirable that all quantitative ecological studies on living foraminiferids should be based on samples of a standard size and that this standard size should be in terms of surface area of sediment. In the past so called 'quantitative studies' have been carried out on unequal samples, samples of equal dry weight or samples of equal volume. Walton (1955) summed up the position very well, "Most ecological work on Recent Foraminifera is aimed at determining their distribution and relative abundance in modern sediments, which is a function of numerous and complex ecological factors. Assuming that Foraminifera live at, or just below, the sediment - water interface the natural measure of populations for

Figure 27: The fishing boat

comparative purposes should be number of species per unit area. Assuming that each environment is supporting the maximum number of Foraminifera possible, referring the population to any base other than available living space appears to be artificial".

Therefore, it was decided during the early part of this study that a sampler was needed that could take sediment samples of a known surface area. Consideration of the sediment samplers available at this time showed that no one design was entirely adequate. With the various grabs and dredges one cannot determine the area of the sediment obtained. Various types of corer, particularly the Phleger corer, have been, and still are, very popular but they have certain disadvantages. If they enter the sediment obliquely the area of sediment will not be the same as the cross - sectional area of the core tube and there is no way to allow for this. In addition, this type of corer only operates satisfactorily in soft sediments, they rarely function in sandy sediments. Schafer (1967) also considered the disadvantages of the Phleger corer and noted that it causes a pressure wave in the water in front of it which disturbs the sediment surface before the sampler hits the bottom. This may result in the floating off of epifaunal foraminiferids. Schafer proposed that SCUBA divers would be more useful to take samples but they would be limited to a certain maximum depth and sampling over a wide area would probably take a good deal of time.

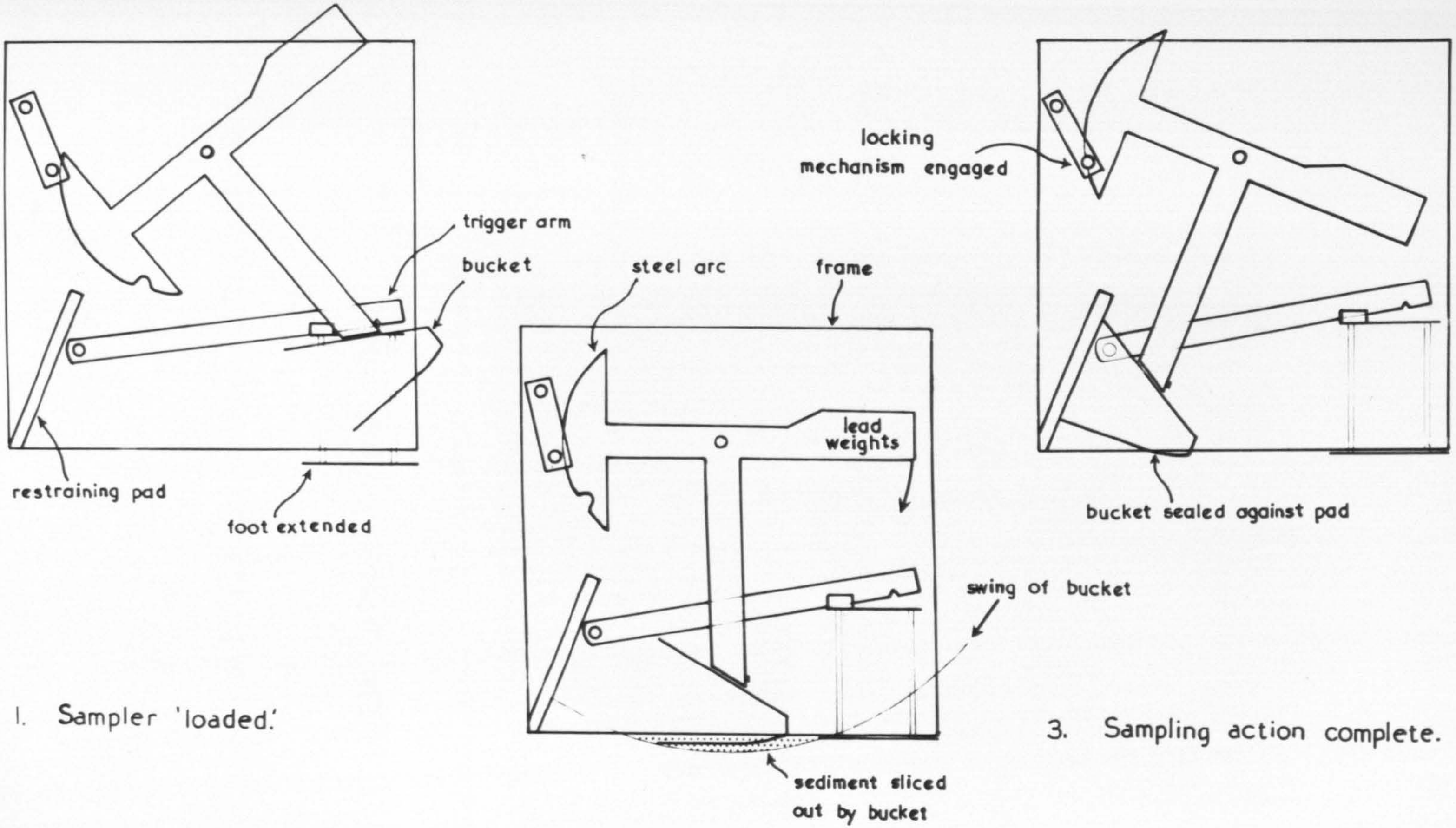
The sampler eventually selected for the Ebro delta study was one which works on a slicing principle, functioning efficiently in either muddy or sandy sediments. The author constructed the sampler following an original design of Dr. J.W. Murray. It was made considerably smaller than Murray's original model, partly because it was not envisaged that sampling would extend to any great depths of water and partly for ease of transport and handling on a small boat. Murray has not yet described his design and so a brief description will be given here to demonstrate how the sampler works.

The sampling device is incorporated into a cubic frame (figures 28 and 29). A 'bucket' of known dimensions is slid onto an arm which is free to swing about a pivot by means of a weight system. To 'load' the sampler before lowering to the sea floor, the bucket arm is pulled back so that a small flange on the arm engages a notch in the 'trigger arm', (see figure 28. 1). This holds the bucket back until the frame reaches the sea floor when the 'foot', which projects slightly below the frame, pushes up the trigger arm so releasing the bucket, (figure 28. 2). The lead weight system then causes the bucket arm to swing about the pivot so that the bucket slices into the upper layers of sediment finally coming to rest against a soft restraining pad. At the same time as the bucket hits the pad a bar engages the notch in the 'steel arc' which effectively locks the bucket against the pad for transport through the water to the surface, (figure 28. 3).

The maximum depth of the slicing arc, assuming that the frame settles on the sea floor, was fixed at 1.5 cm. In practice, the sampler usually sinks slightly into the sediment, the depth of sinking varying with the softness of the sediment, and so the maximum depth of cut is usually a little deeper. This is unimportant since the surface area of the sediment sampled can always be calculated once the volume of the sediment is known. A graph was constructed for this purpose (figure 30).

The procedure for sampling was carried out as follows. At each station the sampler was lowered to the sea floor and left for about 40 seconds to allow the bucket to slice through the sediment and lock against the restraining pad before being winched or hauled to the surface. It was carefully handled onto the boat and turned on end so that the open end of the bucket was uppermost. The locking mechanism was disengaged and the bucket slowly

Fig. 28. Diagrammatic representation of sampler mechanism.



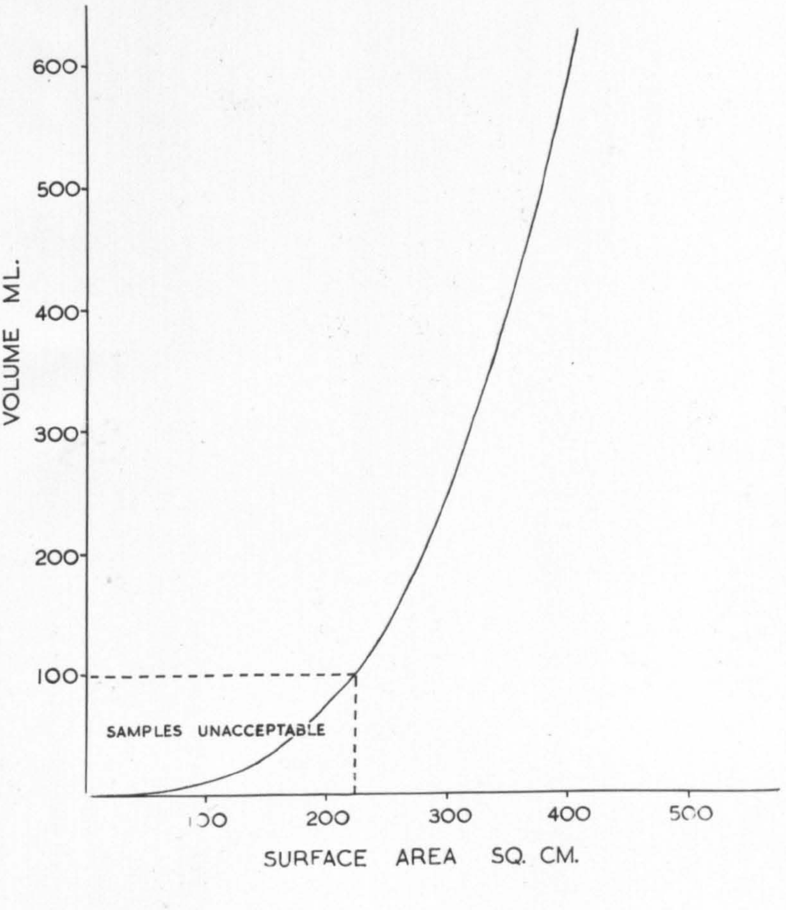
1. Sampler 'loaded.'

2. Sampler in action on sea floor.

3. Sampling action complete.

Figure 29: The sediment sampler

FIG. 30. GRAPH FOR READING OFF SURFACE AREA OF SEDIMENT SAMPLES



slid off the arm taking care not to spill any of the water contained in it. The water was then poured through a 200 mesh sieve to catch any foraminiferids that may have floated off the sediment surface with the disturbance caused either by the sampling action or during transport to the surface. The bulk of the sediment was scraped from the bucket into a polythene bottle and any small remaining traces were washed into the sieve and finally the sieve contents were transferred to the bottle. 98% alcohol was added, with at least as much alcohol as the combined volume of sediment and water, and the bottle shaken to thoroughly mix in the alcohol so that the protoplasm of the foraminiferids alive at the time of collection would be preserved. Finally, the bottle was labelled and stored for transport and the bucket and restraining pad on the sampler carefully washed to avoid contamination of subsequent samples.

The instability of the boat frequently made sampling very difficult. Handling a heavy sampler was very precarious on a rolling deck, but even more irksome was the drifting of the boat whilst sampling. The boat's buoyancy meant that it drifted feely in even the slightest seas. Corrective measures such as running the boat very slowly against the sea did not prove entirely successful. The result of drifting was that the sampler was not lowered vertically and consequently if often fell on its side on the sea floor and did not 'fire'. At many stations the sampler had to be lowered several times before a sample was obtained, and in a few cases a station had to be abandoned without a sample. Occasionally a traverse had to be abandoned altogether when the sea was particularly rough, and because of a tight budget and time limitations, it was not always possible to complete the traverse on another day. Off the river mouth in spring there was a very strong current resulting from the outflow of water and boat drift here was considerable.

Consequently the river mouth traverse in the spring produced few samples. Outflow was considerably reduced in the summer and sampling was more successful.

Water sampling

At most stations bottom water samples were taken for salinity determination. A bottom water sampler was constructed by the author based on the design of Murray (1962) and this was lowered simultaneously with the sediment sampler to take a water sample as close as possible to the position of the sediment sample. At the beginning of the summer 1967 (SU) survey it was discovered that the sampler was not functioning as it should be, due to a defect in construction rather than design. This method of water sampling was therefore abandoned and bottom samples were obtained from the water contained in the bucket of the sediment sampler after passing it through the sieve. The seal of the bucket against the restraining pad appeared very effective and so there was negligible contamination with surface and intermediate water in the passage from the sea floor to the surface. An advantage of this method is that it ensured that the water sample came from directly above the area of sediment sampled. There is a slight possibility that as the sampler was lowered to the bottom the bucket retained sea water from near the surface. More likely, however, water was continually circulating in the bucket as it was lowered and the water contained in it when it was brought to the surface was true bottom water.

Surface water samples were also taken in certain places, particularly in the area around the river mouth where there is considerable variation of surface salinity. Small glass bottles were used to contain all water samples; these were carefully sealed and labelled ready for transport back to the laboratory.

Temperature measurements

Frequent temperature measurements were made along all traverses by means of a thermometer. Surface temperatures were measured directly while bottom temperatures were measured by taking the temperature of the bottom water samples as soon as they reached the surface. Hauling or winching the samples from the sea floor took very little time and it is not considered that any measurable temperature change would have occurred during that time. All measurements were conducted in the shade to prevent any slight rise due to direct sunlight.

Depth measurement

Depths at each station were measured and recorded by means of a Marconi 'Inshore Ferrograph' echosounder (figure 31). This is a small model powered by a 12 volt car battery and has an effective range down to 180 feet (55 metres). The makers recommend that the transducer of the echosounder be fitted to the central region of the hull of the vessel and fared in. This, of course, was not possible on the fishing boats and an alternative system had to be improvised. The transducer was firmly fixed to the end of a length of timber and the transducer cable stapled along its length. The timber itself was lashed securely to one side of the boat amidships so that the transducer was in the correct attitude and about 1 m. from the surface of the water. Much to the surprise of Marconi Instruments Ltd. this system worked very well indeed and good depth records were obtained in all but the heaviest seas. In rough weather the boat rolled a great deal and the pulses emitted from the transducer at a shallow angle did not reach the sea floor. Naturally, therefore, no echoes were picked up and no depth record obtained. When this occurred at a sample station, a metre scale plumb line was lowered and the depth read off.

Fig. 31. Echosounder equipment.

Station plotting

The greatest difficulty associated with sampling was in fixing the position of the sampling stations. The fishing boats had no system whatever for position fixing and it was necessary to relate position at sea to landmarks on the shore. However, this was never entirely satisfactory because of a number of reasons:

1. Inaccuracy of the available maps.
2. Bearings taken by compass or sextant are only accurate to within something less than 1°.
3. The delta is exceedingly flat and there are very few visible landmarks anyway.
4. On a sunny day the heat haze over the land obscured such landmarks as there were from as little as 2 km. from shore.

A method was devised for fixing the position of stations as follows. For each traverse a landmark was chosen on the shore that was either actually on the maps or could easily be fixed on them, such as the lighthouses along the delta front. The traverse was then begun from the chosen landmark on a fixed compass bearing. Termination of a traverse depended on a number of factors including the depth of water reached, the weather, the distance from shore etc. A sample was then taken at the end of the traverse. The position of this station was obviously along a line on the map drawn out from the landmark on the appropriate corrected bearing, but its distance from the shore could not be determined accurately by bearings.

Instead, the echosounder was used as a time / distance measure. The recording apparatus of the echosounder incorporates a rotating drum which winds on the recording paper at a constant rate. An experimental traverse was run close in and parallel to the coastline so that distances could be measured reasonably accurately from a map. Throughout this traverse the boat maintained a constant speed and for a measured horizontal distance a certain length of recording paper in the echosounder was used up. It was then calculated what horizontal distance a unit length of recording paper represented with the boat travelling at that particular speed. Once this was established it was a relatively simple matter to measure the total length of recording paper used on any traverse and relate it to a horizontal distance so that the actual length of the traverse could be determined. Once the farthest station on the traverse was fixed, samples were taken at regular intervals, using the echosounder as a measure, and with the boat travelling at the same speed, back towards the landmark from which the traverse originated.

It is acknowledged that this method of station plotting is by no means wholly satisfactory but it is the best that could be achieved with the equipment available. Compass courses were followed as accurately as possible, probably to within ± 1°, and appropriate allowances were made for the run of the sea. This method fixes stations nearshore reasonably accurately, but accuracy decreases away from shore. Stations farthest from shore are probably plotted only to within ± $\frac{1}{2}$ km. However, as will be discussed in the section on significance of samples, a high degree of accuracy is not considered necessary for plotting offshore samples.

Station plots and traverses for the different surveys are illustrated in figure 32.

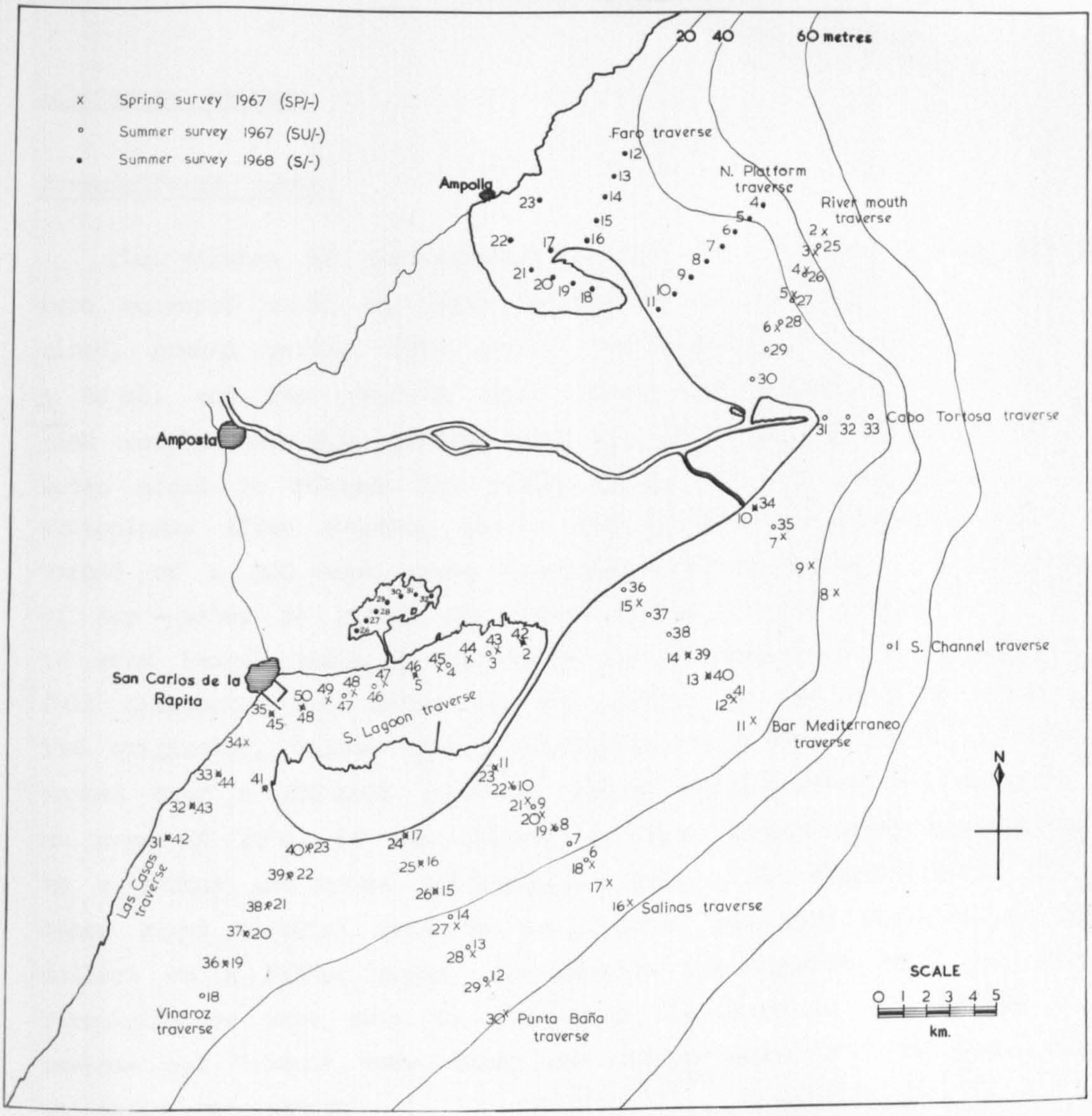


Fig. 32. Echotraverses and station plots.

Laboratory methods

Foraminiferid sample

The volumes of the sediment samples in their settled condition were measured still in their bottles by reference to a similarly sized, graded bottle. This method was probably accurate to within ± 10 ml. and its rapidity amply repaid any small loss of accuracy. Each sample was then emptied into an aluminium container and some water added to restore the water content of the foraminiferal protoplasm. After standing for a few minutes, the sediment was washed on a 200 mesh sieve (aperture 0.076 mm.) with a gentle jet of tap - water to remove the finer sediment. The residue was left in rose Bengal stain (1 gm./litre) for a period of 45 minutes. A full discussion and review of this method of staining is given by its originator, Walton (1952). Following this, the sample was again washed over a 200 mesh sieve to remove excess stain and dried in an oven at 70°C. It was allowed to cool before being transferred to a beaker and carbon tetrachloride added. The foraminiferids and other light material rose to the surface and were decanted off to collect on a filter paper. The process was repeated until no more foraminiferids were seen to rise from the residue. Finally the residue and 'float' were dried and stored separately in glass tubes to await examination.

A portion of the sample float was separated for examination of the living foraminiferids as follows. From the measured volume of the sediment, the surface area was obtained by reference to a graph (figure 30). The foraminiferid float was weighed and the equivalent of 50 sq. cm. surface area of sediment calculated and weighed off. It was discovered that a 50 sq. cm. sample was the most convenient size for counting; the more popular 10 sq. cm. sample produced very small counts of the living foraminiferids that did not adequately portray the proportions of the species.

The 50 sq. cm. portion was examined under the microscope and species of foraminiferids that were stained pink were listed and their numbers counted. Staining was occasionally not decisive and it was necessary to use discretion in deciding whether or not a particular individual was alive at the time of collection. For example, a few individuals exhibited a bright green colour, possibly due to bacteria or algae living within the test, and these were considered as 'living' forms. Lutze (1964) also recorded this phenomenom. He noted that living specimens of Cribrononion turned green when the staining solution was added, and that green specimens should therefore be counted as living. Many specimens, particularly miliolids, did not show the stain colour through the test but only a pink colouration around the aperture. In these cases, and in any case where there was any doubt, the test was broken open to see if there was any properly stained protoplasm within. With most individuals, however, it was comparatively straightforward to decide if they were living or not. A total of 38,906 individuals were counted from the three surveys and many specimens were mounted on slides for further examination.

For counts of the dead population, a representative portion of the float was taken for examination. All empty tests were identified and counted; 250 - 300 individuals were counted in all. This number was selected since it was found that it was the minimum number that needed to be counted to give a reasonably accurate representation of the relative abundance of the component species. Phleger also found this total to be the most convenient and in his book (1960) he states "The accuracy obtained by counting a fraction of the population larger than 300 individuals increases only at a very slow rate".

Samples from cores were processed in much the same way as the standard sediment samples except that the staining with rose Bengal was omitted. In a few cases the muddy sediments had dried out and become very hard. These were left to stand in water as before but a few flakes of sodium metaphosphate were added to help break down the clays. Foraminiferids were again floated off by carbon tetrachloride flotation and after drying were counted in the same way as the dead populations.

Water samples

The salinity of each water sample was determined by the standard method used by water - supply chemists. In fact, it is impossible to determine directly the salinity of a water sample by chemical methods, and it has to be determined indirectly by first determining the chlorinity.

Chlorinity is a measure of the chloride ion content and was defined by Sverdrup, Johnson and Fleming (1942): "The number giving the chlorinity in grams per kilogram of seawater is identical with the number giving the mass in grams of 'atomic weight silver' just necessary to precipitate the halogens in 0.3285233 kilograms of the seawater sample". This was introduced to make determination of chlorinity independent of changes in atomic weight.

The relative proportions of the various chemical components of seawater are constant even though the absolute concentrations may vary and so there is a constant relationship between chlorinity and salinity which can be expressed as follows:

$$\text{Salinity} = 0.03 + 1.805 \times \text{chlorinity}$$

The reagents used in the salinity determinations were made up as follows:

Silver nitrate solution: 4.791 gm. Analar silver nitrate was dissolved in distilled water and made up to 1000 ml.

Potassium chromate indicator: 5 gm. potassium chromate were dissolved in distilled water and made up to 100 ml.

1 ml. of the seawater and 100 ml. of deionized water were pipetted into an evaporating basin and 1 ml. of the potassium chromate indicator added. The mixture was stirred and titrated with the silver nitrate solution with continual stirring. The silver nitrate causes a white precipitate and titration was continued until a slight pink or red colour was noticed. This colouration is due to the formation of silver chromate and indicated that excess silver nitrate had been used. The volume of silver nitrate solution used was read off and recorded with 0.2 ml. subtracted to allow for the excess silver nitrate.

The silver nitrate solution had been standardized so that 1 ml. of it was equivalent to 1 mgr. of chlorine as chloride. The salinity was then easily determined from the chlorinity as indicated previously:

$$\text{Salinity} = 0.03 + 1.805 \times \text{titration figure}$$

At least two titrations were carried out on each water sample until subsequent results were reproducable to within 0.1 ml.

Recording of information

In the field samples were labelled with a code for the appropriate survey followed by a number. Codes were as follows:

Reconnaissance survey - ED/
Spring 1967 survey - SP/
Summer 1967 survey - SU/
Summer 1968 survey - S/

In the field, positions of the stations were plotted on charts and details of the stations and other observations were recorded in field notes. In the laboratory, data cards were established for each station and all the information from the field notes were transferred to them. All station data is recorded in Appendix 1. Details of foraminiferids and their counts were recorded on separate data sheets, one for the living and one for the dead population. In this way data was readily available for closer examination, plotting etc. All population data is recorded in Appendix 2.

Significance of foraminiferid samples

A great deal of information can be derived from quantitative studies on foraminiferid populations. Most workers now realize the importance of taking samples of unit size, but few have paid much attention to the question of adequate sampling of a study area. It has always been assumed that a sample is not only representative of the sampling site from which it was obtained but also of the general area from which it comes.

This assumption was tested in the Ebro delta study by taking a second sample at three selected stations to see how closely they resembled the first samples. The purpose of the test was to determine how homogeneous the foraminiferal population was over a short distance. As the sampler was lowered twice in the space of a few minutes, the two samples at each station were probably only a few metres apart. The sample pairs are compared in table 1 and the foraminiferal data is recorded in Appendix 2. In both lagoon and inshore stations there is a considerable difference in the standing crops and the numbers of species in the pairs. This suggests that there are appreciable differences between the populations in the pairs, but examination of the component species shows

TABLE 1

Station	Depth	% SI	No. species	St. crop	α index	no. of species not in other #	no. of indivs. of these species
SU/12A	36m.	84	36	574	8.5	7	9
SU/12B	36m.		34	644	7.6	5	10
SU/17A	6m.	83	11	70	3.1	0	0
SU/17B	6m.		16	148	4.4	5	6
S/19A	3m.	91	16	408	3.3	7	26
S/19B (lagoon)	3m.		11	240	2.4	2	6

Comparison of sample pairs.

that each pair has many species in common. In addition, the relative abundance of the dominant species is very similar and accounts for the high percentage similarity indices. (A full explanation of percentage similarity indices is given in chapter 8, section b)). In the offshore sample pair, both standing crop and number of species are similar. The percentage similarity index between the two samples is also high and the only differences between the two samples are in the rarer, less important species. The relative abundances of the main species are very similar.

This brief survey suggests that standing crop and number of species per unit area vary much more over short distances nearshore, although the relative abundance of species remains much the same. Offshore standing crops and numbers of species are steadier over short distances and probably only vary gradually over wider areas. This would confirm that samples are adequately spaced offshore and that they are representative of fairly large areas. Nearer the landward influence, populations are much more variable in terms of absolute numbers per unit area but the fact that the relative proportions of species do not vary a great deal over short distances probably means that sampling is adequate is these areas also. Further confirmation of the adequacy of sampling comes from the distributions of species described in section c) of chapter 8. These invariably follow steady trends and so the pattern of sampling in all areas must have been sufficient to bring this out. Had sampling been inadequate, abundance of species would have varied much more from station to station and definite distribution patterns would have been difficult to observe.

Phleger (1952) stated that his foraminiferal samples from the Gulf of Maine were representative of the areas from which they were taken because the distribution of species is not haphazard but has localized centres, or highs, and decreases away from these highs in an orderly manner. Walton (1955), in his study of the foraminiferids of Todos Santos Bay, Baja California, found the highest rate of variation of populations in depths less than 50 fathoms; in deeper water fluctuation diminished. He discovered that standing crops in the marshy conditions over Estero de Punta Banda varied from 0 to several hundred over a few feet or even inches. Open ocean species occured abundantly over depth ranges of hundreds of fathoms and distances of several miles so that samples from this environment could be spaced over greater intervals and still adequately represent the populations. Walton based his bay samples on a one mile grid which he thought adequate, but he recommends closer spaced samples for marginal marine environments.

Buzas (1965), working on samples from Long Island Sound, found that the percentage distribution of the foraminiferid species was meaningful and repeatable which suggested that his samples from the Sound adequately represented the distribution of foraminiferids in the area. He also took sample pairs for comparison and concluded that species proportions were fairly homogeneous in the offshore area.

Shifflet (1961) obtained close - spaced samples from the Heald Bank, Gulf of Mexico, and recorded considerable variation of species and standing crop. She recommended that perhaps samples should be much closer spaced than those presented in most ecological studies on foraminiferids. However, her data is not as reliable as it might be because of the very small size of her counts. Lynts (1966) has also studied the variation of standing crop over short lateral distances. He took closely spaced samples in Buttonwood Sound, Florida Bay and found that there was generally little variation over short distances. He calculated that most foraminiferal micro - environments extend for at least 30 sq. m. In addition, he obtained further information from Shifflet concerning the Heald Bank populations and found that micro-environments there extended for at least 2900 sq. m. This he suggested reflected the more stable conditions there, compared to Buttonwood Sound.

The subject of micro-environments needs close examination in the future. It may well be that species of foraminiferids have certain micro-environmental preferences such as crests or troughs of ripples, around pieces of organic debris etc. Only very detailed sea floor examination and close sampling will bring this out. However, with more general ecological work such as the present study, micro-environments cannot be considered. As foraminiferal distributions on the sea floor are probably clustered rather than random, Dennison and Hay (1967) advise as large a sample as possible to minimize the risk of sampling any isolated micro-environment that would not be a true representation of the whole foraminiferal population around that point. The sediment slicer has the advantage here over the corers because it takes a sample of much larger surface area. Samples of less than approximately 100 ml. volume were not accepted for analysis because of the possibility of inaccuracies; only larger samples were retained in the field. However, at two stations, SP/4 and S/13, only very small samples could be obtained, and although these have been processed, their foraminiferal data is not strictly valid.

A feature which could question the validity of the 'surface area' samples is the depth at which foraminiferids live in the sediment. Myers (1942) found that Elphidium crispum could not free itself when buried in sediment to more than 5 - 7 times its test diameter. Following this work it was assumed that most foraminiferids were epifaunal or living only in the top 1 cm. or so of the sediment and all quantitative studies have been based on samples from the top layer of sediment. However, there have been several studies in recent years to suggest that foraminiferids can live at considerable depths in the sediments. Richter (1961) reported *Nonion depressulus* living down to 4 cm. below the sediment surface, and (1964) *Elphidium selseyensis* living in depths from 0.5 - 6 cm. Boltovskoy (1966) carried out a study on the depths at which foraminiferids could survive in sediments. He took several cores and discovered that although the greatest numbers of species and individuals lived in the top 0 - 2 cm., there were almost as many species at 4 - 6 cm. Numbers decreased with further depth in the sediment, but a few individuals were found living as deep as 16 cm. Brooks (1967) analysed the occurrence of *Ammonia beccarii* at various levels and produced the following results:

Depth level in sediment (cm.)	1	2	3	4
Mean no. of individuals per ml. of sediment	4.8	4.8	4.1	3.1

It does appear that present sampling techniques may be inadequate if the above trends are at all typical. It is possible that many species are infaunal and that different species may prefer different depths in the sediment, just as they have other ecological preferences. Sampling of the top centimeter or so of the sediment may not give an accurate representation of the foraminiferal population at that point. Obviously, a good deal of work is necessary to investigate this subject.

In summary, it seems that the variation of populations over short distances follows the pattern brought out by more general studies on wider spaced samples; i.e. there is more variation in populations close to the shore and increasing stability offshore. Some authors have advocated that closely spaced samples are necessary in nearshore environments to adequately represent the populations. However, it is considered that this should only be necessary in really extreme environments; in nearshore stations around the Ebro delta there is variation of standing crop over short distances, but relative abundance of species is fairly steady. There is generally no extreme difference between any adjacent stations and Phleger's assertion that the distribution of species decreases gradually away from local 'highs' seems to hold true. Sample stations are approximately 1 km. apart off the delta flanks but are closer spaced in the lagoons, and closer still in Encanizada. It is thought that this sampling pattern, in terms of spacing, is entirely adequate to give a good representation of foraminiferal populations around the Ebro delta.

Errors

As a quantitative study has been undertaken and a large amount of numerical data presented, it is worthwhile considering possible errors that may have occurred during the amassing of this data. Errors that may possibly have occurred during processing or counting of samples are assessed.

The measurement of the sediment sample is probably accurate to within ± 10 ml. and Murray (1968) considered that the conversion of volume to surface area was accurate to within ± 3%. It is possible that some foraminiferids are lost or destroyed during processing of the sediment samples, but probably too few to make any difference to the population data. Very small juvenile individuals (less than 0.076 mm. diameter) will pass through the sieve but these are probably few and they would be impossible to identify.

The counting process is where the larger errors occur. The 'human' factor cannot be eliminated during counting and it is likely that several specimens are missed and occasionally one may be misidentified. Consistency of counting was checked: the portion of the float from sample SU/21 representing 50 sq. cm. was counted three times producing the following results:

Count	1	2	3
Number of species	36	34	35
Standing crop	356	348	362

The accuracy of counting the 50 cm^2 portion can be calculated from these results to be about ± 3%.

Another factor investigated was whether the 50 $cm.^2$ portion was really representative of the foraminiferal float as a whole. Three separate portions from sample SU/21, each representing 50 $cm.^2$, were counted and compared:

		Portion A	Portion B	Portion C
	Portion A	$\underline{36}$ $\boxed{356}$	82%	86%
Sample SU/21	Portion B		$\underline{38}$ $\boxed{415}$	86%
	Portion C			$\underline{37}$ $\boxed{421}$

$\underline{36}$ = number of species
$\boxed{356}$ = standing crop
81% = %. similarity index

The results demonstrate that separating a portion of the float for counting may produce some inaccuracy; the different counts were only reproducable to ± 15% (in terms of standing crop) and ± 4% for the number of species. Variations in the similarity indices are the result of fluctuation of rare species, usually only comprising a few individuals.

For counts of the dead population, accuracy increases with the size of the count but after about 250 - 300 individuals accuracy only increases very little with additional numbers counted:

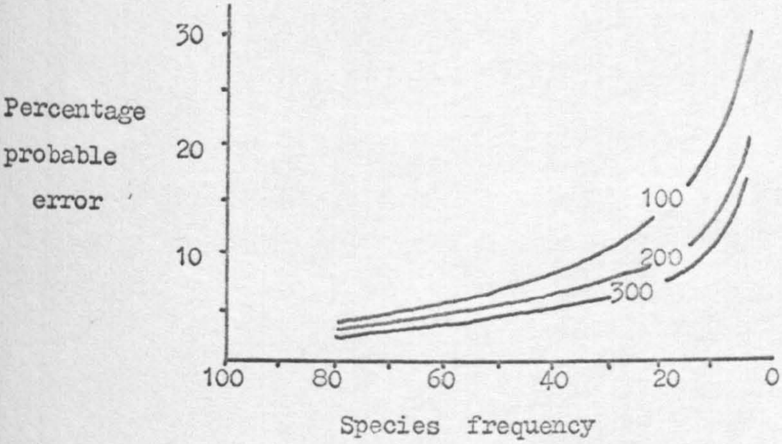


Figure 33: Probable error of a given frequency, counting 100, 200 and 300 individuals. (From Phleger 1960).

Dryden (1931) showed that with counts of this size (250 - 300) the accuracy that could be expected was ± 20% for factors comprising more than 5% of the total. For factors comprising less than 5% the accuracy was less reliable.

It is estimated that the quantitative counts of foraminiferids probably represent the true abundances to within 20 - 25% both for the living and for the dead populations. Although this margin of error appears large, it is not considered to be prohibitive. Accuracy is very difficult to obtain in quantitative ecological studies but it is thought that the accuracy obtained in this study is higher than average.

CHAPTER 7

ENVIRONMENTAL PARAMETERS

It is well known that the distribution of foraminiferids is influenced by factors operating in the environments in which they live and measurement of some of these factors was attempted in the field. Measurements were limited by equipment available, but temperature, depth, salinity and substrate type were fairly accurately recorded (see chapter 6) and information about other variables was obtained by observations in the field.

It is not proposed to include in this chapter a long review of previous work on ecological factors as many authors have already done this satisfactorily (Phleger 1960, Boltovskoy 1965). The nature and variation of each ecological factor measured or observed in the field is discussed, particularly in respect of possible effects on foraminiferids, but the influence of the factors on individual species is considered in chapter 8.

Environmental parameters have been divided into physical and biological factors:

Physical factors:

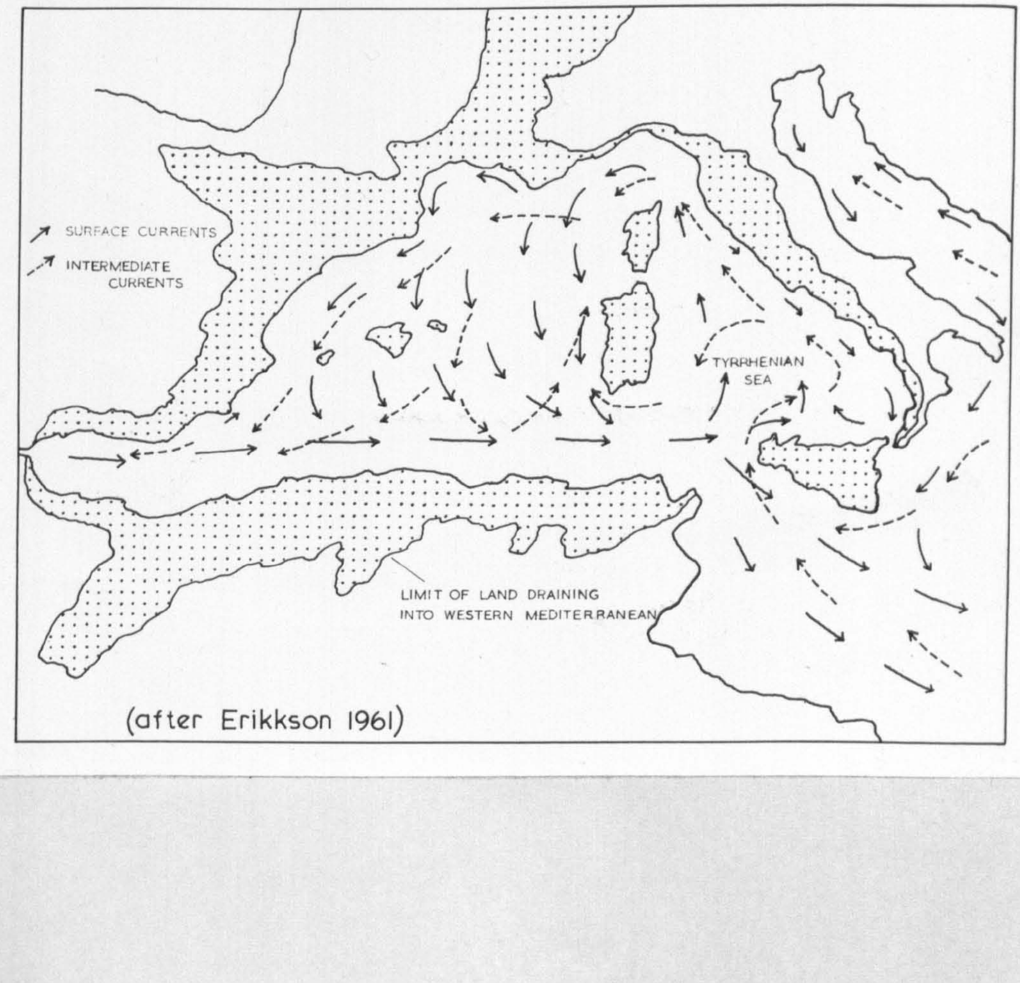
Currents

No equipment was available for current measurements during the Ebro surveys and information has been obtained from other sources.

For most of the year, the warm, dry climate of the Mediterranean area results in low runoff from the land. Heat from the sun causes evaporation from surface water which results in an increase in its density and it tends to sink. Normal density seawater flows in from the Atlantic to make up the water balance and this inflow through the Straits of Gibraltar is the basis of Mediterranean circulation. Atlantic water flows in as a surface current and travels due east until just north of Tunis where it splits. One branch continues into the eastern Mediterranean and another veers north into the Tyrrhenian Sea. The latter branch is responsible for the surface currents in the western Mediterranean, flowing north along the coasts of Sardinia and Corsica and then west and finally south before rejoining the main flow from the Straits of Gibraltar (see figure 34). Water made denser by evaporation sinks to join the intermediate and bottom current system. Currents from the eastern Mediterranean flow into the Tyrrhenian Sea and parallel to the coasts of France and Spain before finally exiting through the Straits of Gibraltar into the Atlantic.

Currents off the Ebro delta flow predominantly north - north - east to south - south - west parallel to the coastline but are not consistent. The Mediterranean Pilot (1963 Edn.) records that currents along this part of the Spanish coast have a consistency of between 25 and 50% and a mean velocity of 16 km. per day. Margalef (1963) also noted that superficial current observations are confused by temporary changes in direction and velocity. Field observations from 1966 - 1968 confirmed this; winds were frequently strong enough to create temporary downwind surface currents. Longshore drift is predominantly to the south although there is evidence for drift in the opposite direction as well. Margalef (1963) also observed that there is frequently a spring inversion of currents resulting in the invasion of very transparent waters from the south and southeast.

Fig. 34. Currents of the western Mediterranean



(after Erikkson 1961)

Surface currents probably have only an indirect effect on the ecology of living benthic foraminiferids; they may influence other ecological factors such as the rate of sedimentation and the supply of potential food. Bottom currents have a much greater influence. Strong bottom currents may determine the nature of the substrate and may winnow away smaller foraminiferids leaving only a population of larger forms or those able to adhere to particles in the sediment.

Depth

Samples from the Ebro delta area were obtained from depths between 1 and 53 m. Some foraminiferids showed distinct depth zonation and although there has been a great deal of work done elsewhere on depth zones and the depth ranges of individual species, relatively little is known about the effects of hydrostatic pressure on their physiology.

Marsland and Brown (1936) discovered that the pseudopodial activity in Amoeba ceased at 250 atmospheres pressure. Pressures greater than 450 atmospheres resulted in the withdrawal of pseudopodia, and one hour's exposure to pressures greater than 300 atmospheres resulted in death of the individuals.

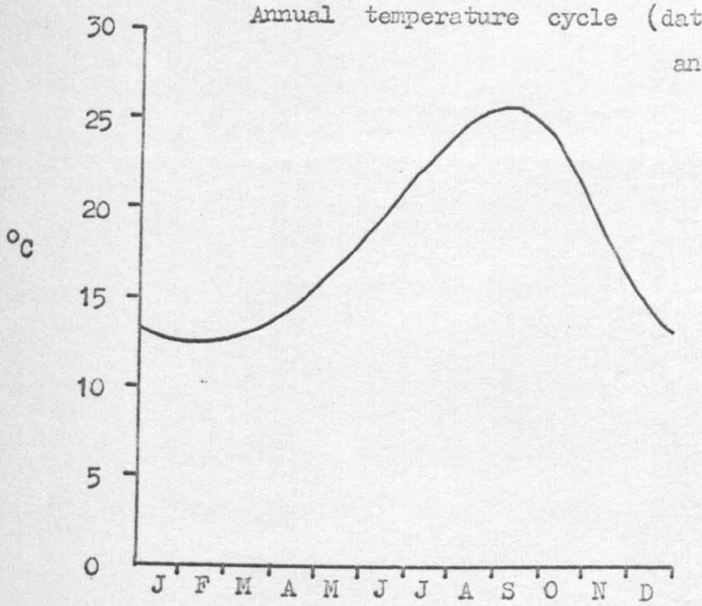
Bradshaw (1961) conducted pressure experiments on Ammonia beccarii var. tepida and found that it could withstand pressures of up to 400 atmospheres for three days, but was immediately killed by pressures of 1000 atmospheres. He noted that shallow water species would be killed by pressures equivalent to those of the abyssal depths, and concluded that the protoplasm of foraminiferids living in the abyss must be specifically to withstand the great pressures at these depths. Nicol (1960) reached the same conclusion and stated "At high pressure, protein molecules are compressed, denatured and altered in structure and chemical activity. In the ocean depths, two factors, low temperature and high pressure, both of which affect biological processes, are acting concomitantly and the animals of the abyss must be genotypically modified to withstand the conditions obtaining there".

It appears from these experiments that most foraminiferids can probably withstand pressures equivalent to a wide range of depth above and below their preferred depth ranges. Depth ranges of many species, certainly those living on continental shelves, are probably determined by other factors that are themselves associated with depth. Only in the greater depths would hydrostatic pressure itself become a controlling factor, and Phleger (1960) suggests a 'pressure threshold' at about 2000 m. depth below which organisms have to be specifically adapted to pressure.

Temperature

Temperature information obtained from the Ebro delta surveys is summarized in figure 35, and isotherms for the whole of the western Mediterranean are shown in figure 36. Open sea temperatures reach a maximum probably in late August, and the highest sea temperature recorded was 27°C. Minimum winter temperatures (from Margalef and Herrera 1964) are in the region of 12 - 13° which means a seasonal range of approximately 14°. Minimum temperatures are attained in February, and following this there is a rapid increase through April to July and the maximum is reached in August and September. There is a very rapid decrease of temperature during October to December until the winter minimum is reached.

During each of the Ebro surveys both bottom and surface temperatures varied only one or two degrees over the whole study area which shows good mixing of waters. There appeared to be no

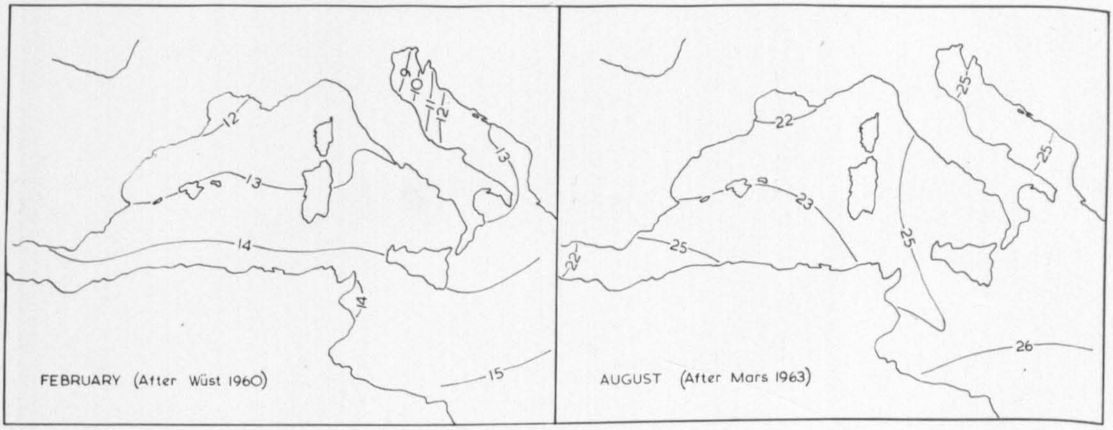


Annual temperature cycle (data from Margalef and Herrera 1964).

	SP Survey Apr. 1967	S Survey June 1968	ED Survey July 1966	SU Survey Aug. 1967
Surface temp. range	13½ - 16	21 - 25	22 - 25	26 - 27
Bottom temp. range	13 - 16	21 - 25	21 - 25	25 - 26½
Mean sea temp. °C	14.5	23.3	23.8	26.1

FIG. 35. Summary of Ebro delta temperature data.

Fig. 36. Surface isotherms of the western Mediterranean



regular pattern of temperature distribution except in the summer surveys when the lagoons tended to have a slightly higher temperature than the open marine areas. For example, in the S/ survey of the northern part of the delta, the lagoon had a temperature of 22 - 23°, reaching 30° in the shoaler parts at the edges, compared with 24 - 25° in offshore areas. Water discharging from the river has a lower temperature than the sea water; in the summer survey the contrast was 24° to 26° and in the spring survey 11.5° to 14.5°. In the latter case it appeared that the coolness of the freshwater had an effect on the surrounding seawater since temperatures around the river mouth and Cabo Tortosa were $\frac{1}{2}$ - 1° lower than farther south.

Surface and bottom temperatures at most Ebro stations were usually the same; only in the deeper water stations was there any contrast, and then it was only of the order of a degree or so. However, Margalef and Herrera (1964) record considerable temperature stratification in three shallow water stations off the southern part of the delta. There was no stratification in the winter, but in the summer they recorded bottom temperatures as much as 9° lower than the surface temperatures in a depth of just over 50 m.

The shallow bodies of water on the subaerial part of the delta have greater extremes of temperature than the open marine areas. In the summer, some of the shallower lakes had temperatures exceeding 35°, and although measurements were not made, it is likely that in winter temperatures in these lakes fell to below those of the sea. They probably also have a considerable diurnal temperature range, particularly in the summer. Encanizada had a mean temperature of 27° in June/July 1968, compared with 23° for the open sea.

Seasonal temperatures are not always consistent from year to year and Bougis et al. (1957) show isotherm maps of the western Mediterranean for three successive summers in which the temperature off the delta varies from >27° to <25°. Mars (1963) shows the Ebro region to have an August surface temperature of 22.5° which seems particularly low.

All the depths sampled off the Ebro delta fall within the 'seasonal layer'; that is, the temperature varies according to the season. Kruit (1955) noted that the temperature in the north - western Mediterranean remains approximately the same at about 13° throughout the year between depths of 100 m. and the bottom of the basin at 2000 m.

Individual species of foraminiferids have different temperature tolerances and laboratory experiments by several workers with various species have confirmed the work of Orton (1920) who stated that most organisms have the following:

A minimum temperature for survival
A minimum temperature for reproduction
An optimum temperature for reproduction
A maximum temperature for reproduction
A maximum temperature for survival

Most species are specifically modified to cope with the temperatures that prevail in the environments in which they live. Thus those species able to withstand the greatest ranges of temperatures are usually found in environments where such extremes are normal, while species living at great depths in the sea where the temperature is constant throughout the year are probably unable to withstand even very small temperature changes. Field evidence for Orton's statements comes from the fact that many species have a seasonal reproductive period when rapid reproduction takes place as the temperature reaches a certain optimum level. Discussion of the effects of temperature on the Ebro delta species is unfortunately limited since no winter data is available for comparison with the spring and summer results, but it can be seen in several cases that there is highest abundance at one particular season, suggesting a temperature preference.

Temperature on a regional scale will determine the species that inhabit an area. Thus a particular species may be a cool - temperate or tropical or cosmopolitan species, whilst on a local scale its abundance will be determined by the proximity of temperatures to the optimum for that species.

Salinity

Bottom water samples were taken at most stations where sediment samples were obtained, and in some cases surface samples were taken as well. Bottom water at all stations, except in Encanizada, had salinities within a range of 37 - 39°/oo which can be classified as 'normal marine'. Mean salinity for the whole of the Mediterranean is approximately 38°/oo compared with the world average of 35°/oo. Apart from off the river mouth, differences in salinity between surface and bottom water were not detected although Margalef and Herrera (1964) discovered a gradation from the surface to the bottom at three stations off the delta. However, the maximum contrast was only of the order of 1 - 2°/oo, and differences of this magnitude were too small to be considered significant with the rough method of salinity determination used by the author. Margalef and Herrera also noted that there was variation of salinity from year to year, and from 1956 - 1962 there was a decrease in salinity coinciding with higher than normal precipitation and runoff from the land.

Salinity only deviated from normal in the marginal marine environments where bodies of water are affected by freshwater from the river. Outflow from the river mouth itself issues as a surface stream of freshwater which gradually becomes mixed with seawater at the edges and underneath the flow. Bottom water samples off the river mouth had normal salinity showing that normal marine water extends underneath the freshwater flow as far as the river mouth bar. Salinity values of 21 - 25^{o}/oo were recorded at the edges of the lagoons while normal marine conditions prevailed elsewhere in the lagoons. Dilution of seawater here is due to small discharge from the numerous drainage channels from the delta. On the spit side of the lagoons there are extensive shoals, and although the water had mostly normal salinity, one value of 42^{o}/oo was recorded in the summer indicating that evaporation of water, leading to hypersalinity, may occasionally take place.

Lakes on the subaerial part of the delta vary greatly in their salinity. Encanizada is virtually a freshwater lake; a value of 2.6^{o}/oo was recorded near the connection with the lagoon at station S/27, but from here salinity decreases rapidly to the east and the easternmost parts of the lake have salinities around 0.6^{o}/oo. Other lakes on the delta behind the frontal beaches have salinities ranging from 8 - 37^{o}/oo. All these lakes are very shoal and each probably varies in salinity from time to time depending on the amount of dilution by water from the river or the rate of evaporation by heat from the sun. Some of the lakes have undoubtedly become hypersaline at times because there were many depressions where lakes had dried and left a thin salt crust on the surface of the sediment.

Different species of foraminiferids are adapted to different ranges of salinity but, as with temperature, those tolerant of wide ranges of salinity are usually found in environments where such ranges are common.

Substrate

Distribution and variation of bottom sediments have already been discussed in chapter 4. There is a difference of opinion among many authors as to the importance of the substrate in the ecology of benthic foraminiferids. There have been many published studies in which the authors have recognized distinct faunas on different substrate types. In the author's opinion, substrate is an important ecological factor and it will be demonstrated in chapter 8 that the distribution of several Ebro delta species is related to the grade of bottom sediment. However, it is not known whether the sediment itself is all important or whether factors associated with it have more influence. For example, several species are confined to muddy substrates but it may be that, rather than having a positive preference for the physical properties of fine grained sediments, they are unable to withstand the turbulent or current - swept bottom conditions associated with substrates of coarser sediments.

Phleger (1960) said that fine - grained sediments generally contain a larger amount of organic material, and thus more potential food, than coarse - grained sediments. Fine - grained sediments may therefore support larger populations than sands, especially where there is a mixture of mud and sand. Boltovskoy (1965) also considered that a mixed fine - grained sediment will support highest populations, the mixture consisting of sand, clay and a little shelly material.

Chemical constituents of the seawater

Apart from salinity, no other chemistry was attempted on water samples. However, relative availablity of dissolved oxygen in the bottom water was assessed by measuring the depth in the sediment of the oxidation/reduction line. This is marked by an abrupt change in colour in the sediment from light brown or yellow to a dark grey or black. A poor supply of oxygen in the waters above the sediment surface results in stagnation and the sediments become black in colour following the reduction of sulphates to sulphides by anaerobic bacteria. Low oxygen content is usually attributable to poor or non - existent water circulation. Oxidation/reduction levels off the Ebro delta vary from 0 - >10 cm. below the surface of the sediment. They are deepest on the delta front platform where there is obviously a good supply of dissolved oxygen available to surface sediments from the currents that flow parallel to the delta flanks. Poor water circulation in the lagoons results in a relatively reduced supply of oxygen and consequently the oxidation/reduction level is rarely deeper than 1 cm. below the surface of the sediment. In Encanizada circulation is even poorer and surface sediments are frequently grey in colour indicating stagnation and low oxygen availablity. Black sediments resulting from oxygen deficiency have a high content of hydrogen sulphides produced by anaerobic bacteria, and it is well known that this limits the distribution and occurrence of many organisms. It seems reasonable to suppose that it is adverse for foraminiferids as well and field records show that very few species are able to tolerate stagnant conditions.

Several authors have pointed out the importance of hydrogen ion concentration (pH), and some species are known to be more tolerant of wide variations than others. These are invariably marginal marine species that are found where fluctuations of pH are most common. Open water species are probably less able to tolerate changes in pH; Zobell (1946) stated that most open water sediments have a pH within the range 7.5 to 9.5. Boltovskoy (1965) observed that cultures of Elphidium macellum and Quinqueloculina seminulum were rendered completely inactive by a lowering of the pH to 7.0.

Other chemical constituents of seawater may affect foraminiferal distributions. Many other marine plants and animals require very small quantities of certain elements and it is possible that the distribution of these is important to foraminiferids. In the open sea, chemical constituents of the seawater are fairly consistent in their concentrations. However, in nearshore areas runoff from the land may locally affect the proportions of the chemical concentrations of the water. Boltovskoy (1956) attributed a 'depauperate fauna' on part of the continental shelf off Argentina to the presence of abnormally high concentrations of lead in the seawater.

Biological factors:

Food

Distribution and availability of food is of prime ecological importance to all organisms. Several workers have correlated high living foraminiferal populations at particular times of the year with maximum abundance of food. Food availablity was not tested around the Ebro delta but it is generally recognised that deltaic areas are very productive because of the large quantities of inorganic 'raw material' being brought down by rivers. Margalef (1963) analysed various features of the phytoplankton in the surface waters around the delta and discovered that populations were higher than in waters farther south down the coast near Castellon:

	Off the delta		Near Castellon	
	Dec. - May	June - Nov.	Dec. - May	June - Nov.
Million cells/m.^{2}	2296	1158	1435	1052
Dry wt. without ashes (mg/m^2)	2450	2350	2230	2010
Chlorophyll (mg/m^2)	5.75	2.71	5.22	2.47

It can be seen that values are highest in the winter - spring period; this is due to the spring bloom of phytoplankton associated with maximum discharge from the river mouth.

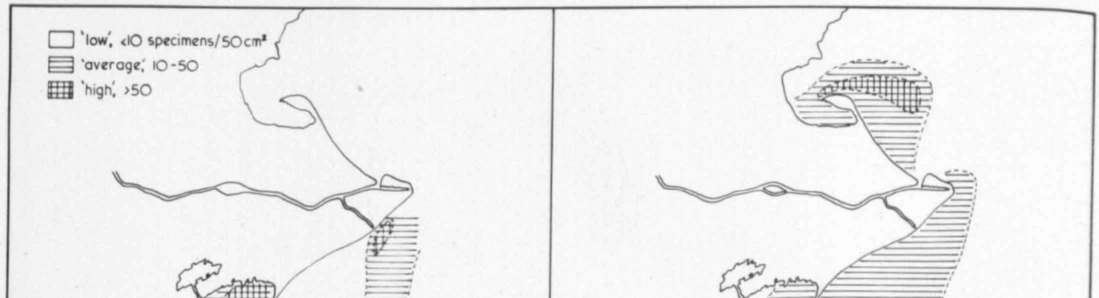
Food requirements of foraminiferids are discussed more fully in the section on standing crop in chapter 8.

Biological competition

No method is yet available which allows observation of animal activities and inter - relations on and within the sediment on the sea floor and it is not possible to reproduce the complexity of the marine ecosystem in the laboratory. However, in most other environments different groups of animals have some effects on each other, either directly or indirectly, and it is reasonable to assume that the foraminiferids are affected by the activities of other animals. Competition for food may occur, particularly when it is in short supply, although many species of foraminiferid are sufficiently adaptable to accept almost any type of organic material as food. Nevertheless, species with similar food requirements may compete with each other, and competition with other animals may also occur.

Several stations in the Ebro delta area had very high populations of juvenile bivalves, and these, and possibly other animals, may compete with the foraminiferids for available living space at or near the surface of the sediment. Counts of bivalves revealed that highest populations are generally in the lagoons, particularly on the weed, and at some stations with sandy substrates on the delta front platform. Bivalve populations are higher in the summer and generally decrease with depth, (see figure 37). Schafer (1967) noted that many animals affect foraminiferids living on or within the sediments, including vertebrates and larger invertebrates. He suggests that local variations in foraminiferal populations may occur where animals such as flounders rest on the sediment and disturb it.

Fig. 37 Bivalve populations



CHAPTER 8

DISTRIBUTION AND ECOLOGY OF THE FORAMINIFERIDS

a) INTRODUCTION

This chapter deals with detailed information on the living foraminiferids. There have been few previous studies on living foraminiferids in the Mediterranean. Kurc (1961) studied the living foraminiferids in the Etang de Thau on the French Mediterranean coast and Blanc - Vernet (1963) examined the fauna of the Gulf of Marseille and distinguished distinct faunas on sand and mud substrates. Other studies have generally only been concerned with the dead populations. Only data from the living populations can be used for valid ecological interpretation of species and the bulk of this chapter is therefore concerned with various aspects of the living populations. The dead population is briefly dealt with in a short section to examine the similarities and differences with the living populations and the extent of post - mortem redistribution of empty tests.

The first part of this chapter is concerned with non - specific characteristics of the living foraminiferids, faunal assemblages, diversity and standing crop, while the later part deals with the ecology and distribution of the most important species. The aims of this later section are to attempt to relate the distribution and abundance of each species to any of the measured or observed environmental factors and to discover any changes in abundance and distribution at different seasons. Although only spring and summer collections were made, differences in abundance between the two are probably sufficient to point to temperature preferences exhibited by individual species. A brief review of their modern and fossil occurrences is also presented, particularly with regard to the European area. The author's collection of European samples (listed in Appendix 3) and faunas examined in the Recent Foraminifera collection of the Protozoa section of the British Museum of Natural History have been used to supplement information in the literature. A summary of the ecological information obtained from the Ebro delta is presented in Table 10 at the end of the section.

b) NON - SPECIFIC FAUNAL CHARACTERISTICS

LIVING FORAMINIFERAL ASSEMBLAGES

The nature and magnitude of the physical and biological factors that operate in a particular area will have a direct influence on the species that can live within it. Therefore areas with differing environmental factors will usually be characterized by distinct assemblages of foraminiferid species. In most cases the same environmental parameters determine sedimentary environments and thus foraminiferal assemblages frequently correspond with sedimentary environments in their areal extent. Many workers have conducted studies in which assemblages have been distinguished and they variously been called populations, faunas, facies, biofacies, etc.

A living foraminiferal assemblage can be defined as a group of populations of foraminiferids living in a particular environment, or part of an environment, which is distinct from adjacent assemblages because of the unique association of physical and biological factors operating in the environment. Distinction from adjacent assemblages is on the basis of species composition or the relative abundance of the same species. Within each assemblage there are usually seasonal variations in the abundance of the component species and often there are changes in the foraminiferids from one part of an assemblage to another. However, such changes are necessarily small and gradational and the assemblage at all times maintains a distinction from neighbouring assemblages.

In marginal marine areas delimitation of foraminiferal assemblages is usually easy; the wider variation of environmental conditions means that there are greater variations in the foraminiferid populations and boundaries between assemblages are relatively easy to detect. Boundaries may frequently be physiographic; for example, the boundaries of a lacustrine assemblage are defined by the edges of the lake.

In the subaerial environments of the Ebro delta, two foraminiferal assemblages are distinguished, marsh and lacustrine. Discussion of these, and other, assemblages follows in which the component foraminiferids are listed and divided into three categories:

1. Those confined exclusively to a particular assemblage.

2. Those that occur in other assemblages but are most abundant in a particular assemblage.
3. Those occurring in relatively low frequencies that are more abundant in other assemblages.

The lists are somewhat long in places but need to be presented for the sake of completeness. The most important species (those frequently occuring with more than 10 % relative abundance) are marked with an asterisk. A summary of the foraminiferal assemblages is given in Table 2 at the end of the section.

Marsh assemblage:

Only one non - quantitative sample was taken from the marsh environment for foraminiferal analysis and it is not known whether the foraminiferids recovered are representative of the marsh assemblage as a whole. The sample, in fact, contained very few foraminiferids but there were equal numbers of living Miliammina fusca and Jadammina macrescens. These both have agglutinated tests and several authors including Phleger (1960) and Parker and Athearn (1959) have noted the preponderance of Textulariina in hyposaline marshes. Living hyaline calcareous species are occasionally reported, but they note that empty tests are very rare and suggest that the low pH associated with marsh conditions causes them to be dissolved. Phleger also observed that many marsh species have surprisingly wide geographical distributions considering that marshes are nowhere near continuous along most coastlines. He suggested that marshes were possibly far more widespread in the Upper Tertiary than they are at present.

Lacustrine assemblage:

The shallow lakes on the subaerial part of the delta have a characteristic foraminiferal assemblage, and following the sedimentary pattern, they are divisible into freshwater and brackish types. The component species are as follows:

Brackish lakes

Category 1	Category 2	Category 3
Reophax moniliforme	*Ammonia beccarii**	*Protelphidium anglicum**
Ammotium c.f. *A. salsum*	*Elphidium oceanense**	
Trochammina inflata		

Freshwater lake (Encanizada)

	*Protelphidium anglicum**	*Ammonia beccarii*
		Elphidium oceanense

In Encanizada, *P. anglicum* usually comprises 100 % of the fauna; the other two species only occur near the connection with the southern lagoon where there is a slightly higher salinity. In the brackish lakes *A. beccarii* (var. 1) is dominant, usually constituting about 80 % of the living population, but the other species vary in their occurrences and relative abundance. Ostracodes are very common in the lakes and frequently outnumber the foraminiferids.

In marine areas delimitation of assemblages is not always easy; the increased stability of offshore marine environments is reflected by smaller changes in the foraminiferid populations. Consequently assemblages tend to have wider areal extents. In offshore areas many authors distinguish foraminiferal depth assemblages but it is thought that most species, particularly those living on the continental shelf, are not directly influenced by hydrostatic pressure. Laboratory experiments (e.g. by Bradshaw, 1961) have demonstrated that nearshore species can withstand considerable pressures. Each species probably has a preferred depth range but control of depth distribution of many species is associated with factors related to depth, such as the base of the seasonal layer etc. Therefore, although depth assemblages may readily be distinguished, it is necessary to consider whether other factors are controlling them apart from hydrostatic pressure itself. The latter probably has increasing significance in much deeper water.

Delimitation of offshore assemblages has usually been carried out by simple inspection of population data, but recently some authors (e.g. Kaesler, 1966, Mello and Buzas, 1968, and Bonham - Carter, 1968) have applied cluster analysis techniques to the detemination of assemblages. Population data is analysed to calculate correlation coefficients between samples and the magnitude of the coefficients reflects the degree of similarity between them. The results are then subjected to cluster analysis and similar samples are grouped into assemblages; all coefficient calculations and clustering procedures can be carried out very rapidly by computer. Such techniques were not utilized for Ebro delta foraminiferal data as it was discovered that, without the aid of other persons, there was insufficient time to become familiar with computer techniques, writing programs etc. to produce acceptable results. In addition, a preliminary survey revealed that no one correlation coefficient was totally satisfactory; most utilize only presence/absence data which means that quantitative data is useless. However, it is acknowledged that once the techniques have been developed and tried, analysis of population data by means of computering is a very rapid method of assemblage delimitation.

The author came across a very simple method by which boundaries between assemblages can be detected. It involves the calculation of a 'similarity index' (hereafter referred to as SI) between samples from relative abundance data. The index was first used by Raabe (1952) in plant ecology and has not yet been applied to foraminiferal data. It is derived from:

$$\Sigma \min (a,b,c, \ldots\ldots\ldots\ldots x) = \% \text{ SI}$$

For any two samples the relative abundance of the component species is inspected. Where a species is common to both samples, the smaller of the abundance values is recorded; the total of all the minimum values for all the species common to both samples represents the % SI. Identical samples have SI = 100 %, while values in excess of 80 % indicate that the populations in question are very closely similar.

An important feature of this index is that it takes into account the relative abundance of species and not just their presence or absence. It is particularly useful for comparison of roughly equally spaced samples along offshore traverses. Within a particular assemblage, % SI's will vary little between adjacent samples but a transition to another assemblage will be marked by lower values. The actual SI values will vary from area to area, depending, among other things, upon the spacing of the samples. However, this is unimportant, the vital point is that boundaries between assemblages can be detected by a relative lowering of values.

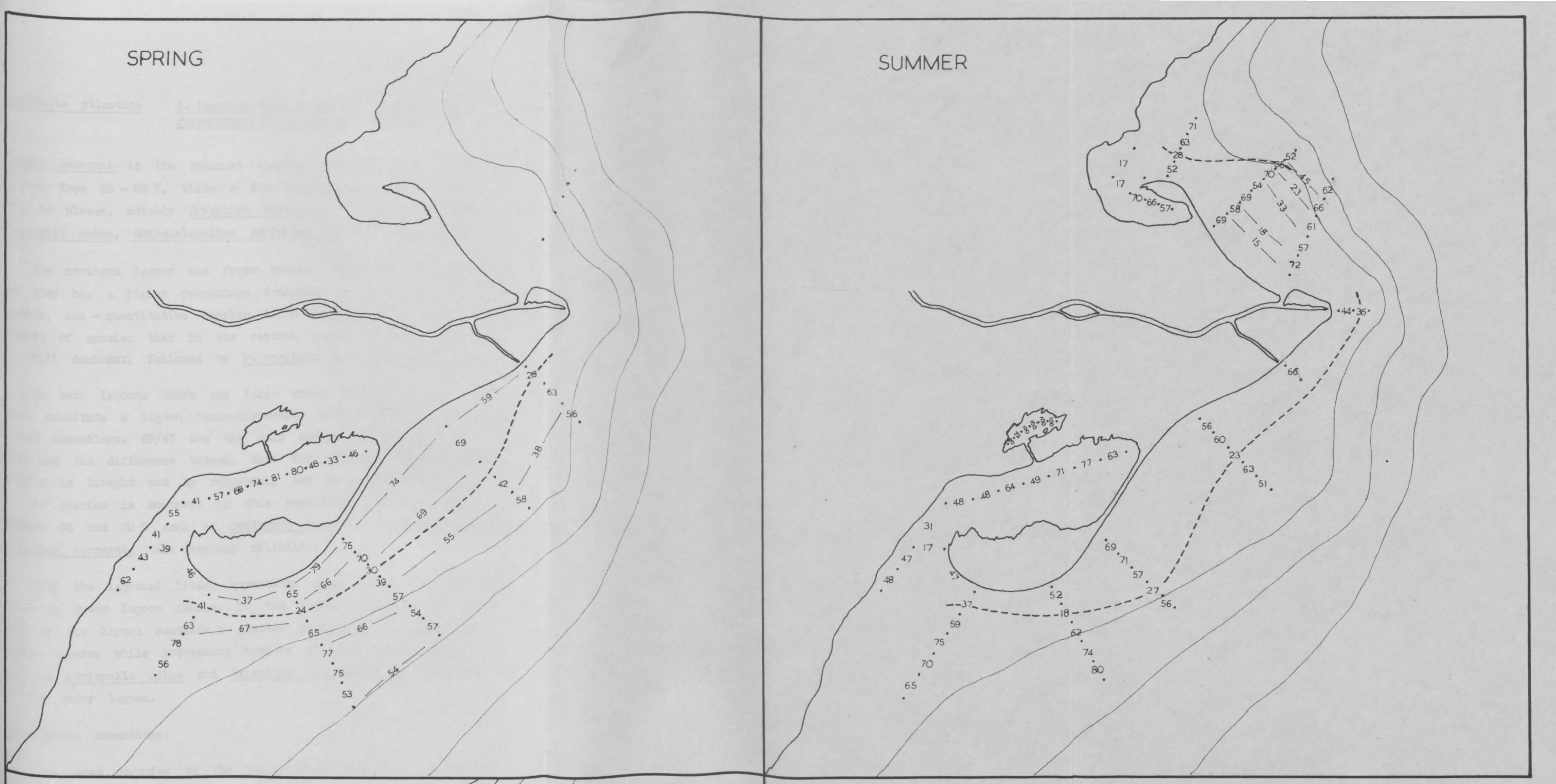
All the Ebro delta samples have been compared by this method and % SI's between adjacent samples are shown in figure 38. In addition to the two assemblages already described, five further assemblages are distinguished in the marine area and are described in the following pages. The areal extent of all assemblages is illustrated in figure 38.

Lagoonal assemblage:

Foraminiferids typical of the lagoons are as follows:

confined to ass

Category 1	Category 2	Category 3
Quinqueloculina sp.	*Cyclogyra incerta*	*Q. schlumbergeri**
Triloculina rotunda	*Buliminella elegantissima*	*Triloculina sp.*
Rosalina c.f. *R. concinna*	*Bolivina pseudoplicata*	*Bulimina aculeata*
R. c.f. *R. mediterranensis*	*Brizalina striatula*	*Elphidium oceanense*
Patellina corrugata	*Hopkinsina pacifica/atlantica*	*Protelphidium anglicum*
Ammonia beccarii var. 2*	*Rotalia perlucida*	*Nonion depressulus*



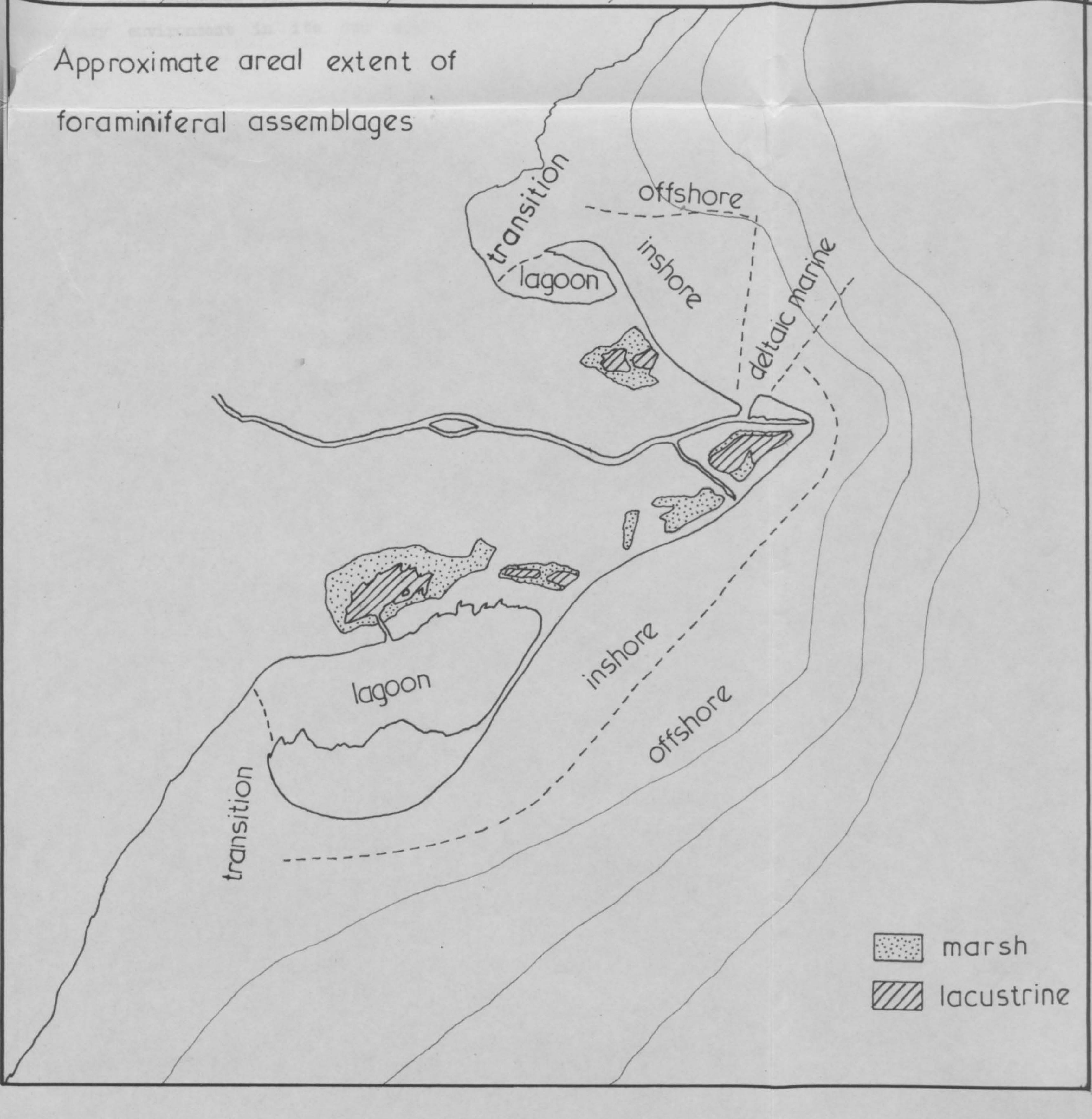


FIG. 38. % similarity indices between stations and foraminiferal assemblages.

Nonionella atlantica

A. beccarii var. *batavus**
Fursenkoina schreibersiana

N. laevigatum
*Nonionella opima**

Ammonia beccarii is the dominant species with relative abundance varying from 20 - 80 %, while a few other species attain around 10 % in places, notably *Brizalina striatula*, *Patellina corrugata*, *Nonionella opima*, *Quinqueloculina schlumbergeri* and *Cyclogyra incerta*.

The northern lagoon has fewer species than the southern lagoon and also has a higher percentage dominance of *A. beccarii*. In both lagoons, non - quantitative samples taken at the edges reveal smaller numbers of species than in the central parts. However, *A. beccarii* is still dominant, followed by *P. anglicum* and *E. oceanense*.

In both lagoons there are large areas covered by weed and these consitute a lagoon 'subenvironment' with a fairly distinct living assemblage. SP/43 was the only sample to be taken on the weed and the difference between this and adjacent 'normal' lagoon samples is brought out by relatively low SI's (see figure 38). No one species is dominant in this population and there are between 10 and 20 % each of *Cyclogyra incerta*, *Triloculina rotunda*, *Patellina corrugata* and various miliolids.

With the lagoonal living assemblage there is a gradation from inner to outer lagoon faunas. In the southern lagoon, the inner part of the lagoon contains a greater proportion of indigenous lagoon species while increasing numbers of open marine species, such as *Nonionella opima* and *Brizalina pseudopunctata*, are found in the outer lagoon.

Transitional assemblage:

The area occupied by the transitional assemblage is not a sedimentary environment in its own right. It is an area just outside each lagoon where several different assemblages converge, but is basically an area in which there is a changeover from lagoonal to open marine faunas. The assemblage contains 'inshore' and 'offshore' elements (see later) plus a few lagoonal species and some forms that are possibly more abundant farther north or south along the non - deltaic coastline. The transitional nature of the assemblage is illustrated by relatively low % SI's between stations over a wide area (17 - 62 %). In addition, there is a preponderance of species of category 3, i.e. species that are more abundant in other assemblages. The typical species are:

Category 1

*Rosalina valvulata**

Category 2

Haplophragmoides canariensis
Elphidium c.f. *E. flexuosum*
Florilus c.f. *F. japonicum*

Category 3

Eggerella scabra
Clavulina obscura
Cyclogyra incerta
Quinqueloculina schlumbergeri
Triloculina sp.
Buliminella elegantissima
Bolivina pseudoplicata
*Brizalina pseudopunctata**
B. striatula *
Bulimina aculeata
B. elongata
B. gibba
Hopkinsina pacifica/atlantica *
Epistominella vitrea
Gavelinopsis praegeri
Asterigerinata sp. *
A. mamilla
'Rotalia' perlucida
Ammonia beccarii *
Elphidium advenum
E. crispum
E. lidoense
E. selseyense
E. sp. 1
Fursenkoina schreibersiana
Nonion depressulus
N. laevigatum
Nonionella atlantica
N. opima *

Dominance of this assemblage is usually by *N. opima* or

B. pseudopunctata, although *Q. schlumbergeri* tends to become dominant on the sandy substrates close to the spits. *Rosalina valvulata* is the only species more or less indigenous to the transition area and it reaches its peak of abundance (14 %) at station SU/44. At the same station in spring *Asterigerinata* sp. is most abundant.

Inshore assemblage:

The % SI values shown in figure 38 bring out and important faunal boundary just offshore from the delta flank coastline. It can be seen that on all offshore traverses SI's vary from approximately 40 - 80 %, but at some point on each traverse there is a realtively low value, from 18 - 40 %, which marks a faunal change. This change marks the appearance of a number of new species over a relatively short distance, 1 - 2 km. The boundary varies in depth from about 9 - 13½ m. in the spring and from 9 - 16 m. in the summer when it reaches its maximum depth along the Salinas traverse. On the northern side of the delta the same boundary varies from 12 - 15½ m. in depth and is slightly farther from the shoreline. However, it is not distinguished off the river mouth where there is obviously a different set of conditions in operation. 'Inshore' and 'offshore' assemblages are distinguished on either side of the boundary, each having its own typical species. The boundary roughly corresponds to the seaward limit of the delta front platform sedimentary environment. The inshore assemblage occupies the area affected by nearshore turbulence and its component species are those able to withstand turbulent conditions. They include:

Category 1	Category 2	Category 3
Quinqueloculina depressa	*Reophax scottii*	*Textularia calva*
Elphidium excavatum	*Trochammina lobata*	*Ammosphaeroidina sphaeroidiniformis*
E. incertum	*Quinqueloculina rugosa*	
Nonion c.f. *N. germanicum*	*Q. schlumbergeri* *	*Q. seminulum*

_N_. c.f. _N. matagordanum_
_Eponides granulata_*

Triloculina sp.*
Asterigerinata sp.*
_Nonion asterizans_*
_Nonion depressulus_*
_N. laevigatum_*

'Rotalia' perlucida
_Ammonia beccarii_*
Elphidium advenum
E. crispum
_E_. c.f. _E. flexuosum_
E. lidoense
Elphidium sp. 1
Bulimina aculeata
Brizalina pseudopunctata

Of the indigenous species (category 1) only _Eponides granulata_ is widespread throughout the inshore assemblage, the others only occur locally. The assemblage has a smaller number of species per sample than the offshore assemblage and the dominant species tends to vary from place to place and from season to season. _Asterigerinata_ sp. is dominant on the southern side of the delta in spring followed by miliolids (chiefly _Q. schlumbergeri_), while in the summer miliolids (again chiefly _Q. schlumbergeri_) are usually dominant on both sides of the delta followed by more local high abundance of _N. depressulus_, _N. laevigatum_, _N. asterizans_, _N_. c.f. _N. matagordanum_, _N_. c.f. _N. germanicum_, _Ammonia beccarii_ and _Reophax scottii_. At the ends of the spits the inshore assemblage grades into the transitional assemblage, while directly off the river mouth it gives way to the deltaic marine assemblage.

Offshore assemblage:

The offshore assemblage succeeds the inshore assemblage with depth off the delta flanks. It marks the introduction of many deeper water species and samples invariably have more species than the inshore assemblage. The larger number of species results in the dominant species having a lower relative abundance than closer to the shore and it is common for there to be two or three species with between 10 and 20 % relative abundance in offshore samples.

The assemblage coincides with the pro delta slope sedimentary environment as far as the latter is sampled, but it is not known how far the assemblage extends out to sea. It forms the first environment away from the nearshore turbulent zone and marks the incoming of many true open shelf species. The typical foraminiferids are:

Category 1

Saccammina atlantica
S. comprima
Reophax c.f. R. fusiformis
R. scorpiurus
Nouria polymorphides
Trochammina c.f. T. advena
Eggerella advena
Q. longirostra
Pyrgo inornata
Florilus scaphus

Category 2

S. difflugiformis
S. lagancula
Textularia calva
T. tenuissima
A. sphaeroidiniformis
Eggerella scabra
Clavulina obscura
Q. seminulum
B. c.f. B. aenariensis
B. spathula
Bulimina gibba *
Reusella aculeata
Uvigerina sp.
Rectuvigerina c.f. R. compressa
Gavelinopsis praegeri
Asterigerinata mamilla
Elphidium advenum
E. crispum
E. lidoense *
E. selseyensis *
E. sp. 1
E. sp. 2
Fursenkoina c.f. F. complanata
Nonionella opima *
Melonis pompilioides

Category 3

Reophax subfusiformis
Haplophragmoides canariensis
Triloculina sp.
Brizalina pseudopunctata *
B. striatula
Bulimina aculeata*
Epistominella vitrea
Valvulineria complanata*
Asterigerinata sp
'Rotalia' perlucida
Ammonia beccarii
Elphidium c.f. E. flexuosum
Fursenkoina schreibersiana
Cassidulina laevigata
Nonion depressulus *
N. laevigatum

Nonionella opima dominates the assemblage at most stations and has particularly high relative abundance to the south along the Vinaroz traverse, while Brizalina pseudopunctata reaches high abundance in places, particularly in the summer. Other species such as Valvulineria complanata (especially in the spring) and Bulimina aculeata (summer) also have local high abundance within the assemblage. The species listed above are those that occur most commonly in the offshore assemblage, but there are many others that occur irregularly and in very low frequencies.

Deltaic marine assemblage:

Directly off the river mouth there is a distinct assemblage controlled by the unusual sedimentary conditions in operation there. No species found there is exclusive to the assemblage; it contains chiefly 'offshore' species in different proportions to their occurrences in the offshore assemblage. However, there are fewer numbers of species per sample than in the offshore assemblage and it appears that not all offshore species are sufficiently tolerant to withstand the conditions of rapid sedimentation.

The boundaries of the deltaic marine assemblage with the adjacent inshore and offshore assemblages are vague since discharge from the river, and hence the area of rapid sedimentation, changes slightly in direction according to the strength and direction of the wind. The assemblage is most distinct close to the shore where several offshore species occur in relatively shallow water; this contrasts with the adjacent inshore assemblage in the same depths. In deeper water sedimentation becomes progressively slower and the deeper faunas are more similar to a normal offshore assemblage. The % SI values between the deltaic marine assemblage stations and those of the northern platform traverse (figure 38) illustrate this feature; they are lowest inshore and increase with increasing depth.

Typical species of the deltaic marine assemblage are:

Category 1	Category 2	Category 3
	Reophax subfusiformis	Saccammina diffluglformis
	Brizalina pseudopunctata*	Haplophragmoides canariensis
	Bulimina aculeata*	Textularia calva
	Bulimina sp. 1	Ammosphaeroidina sphaeroidiniformis
	Epistominella vitrea*	

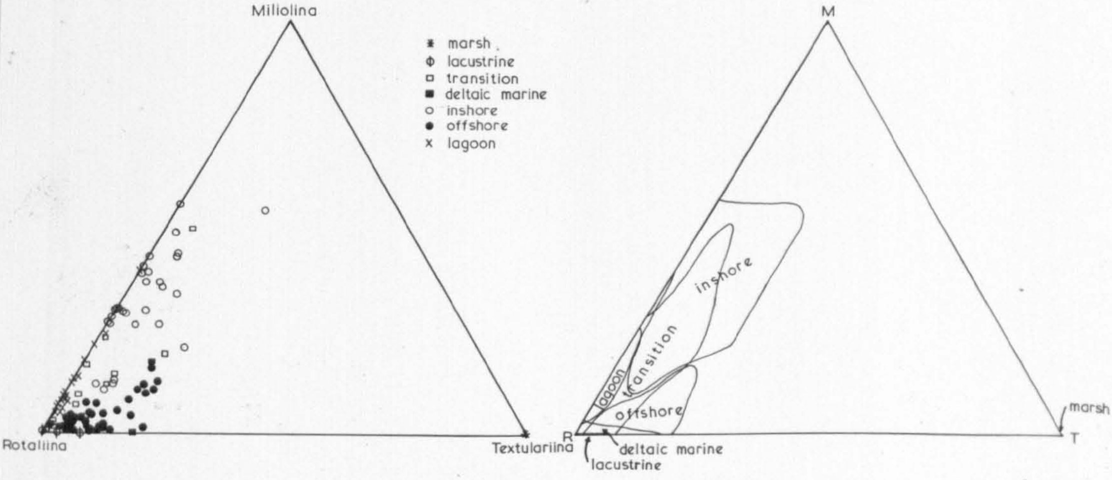


Fig. 39. Triangular plot of population analyses to show assemblage fields.

The high percentages of miliolids in the inshore assemblage result in it plotting higher than the offshore assemblage which has a low miliolid content but a relatively high proportion of Textulariina. The lagoons have a variable percentage of miliolids but always a low proportion of Textulariina, so the lagoon assemblage plots very close to the margin of the diagram. The transitional assemblage covers a wide field embracing part of each of the fields already mentioned. The deltaic marine assemblage has a very low proportion of Miliolina, while the lacustrine assemblages have very few miliolids at all and plot along the base line.

Murray (1968) plotted 201 population analyses from different types of lagoon on a similar triangular diagram. His 'normal marine' lagoons had higher proportions of both Miliolina and Textulariina. However, the only published data on normal marine lagoons available for plotting this field was on two lagoons on the Californian coast, and it is likely that the field is not as wide as it might be.

Comparisons:

Kruit (1955) in his study of the Rhône delta, distinguished several 'microfaunal associations' but his foraminiferal data is not very comprehensive and he did not use staining methods to distinguish living forms. Nevertheless, some analogies can be drawn and it is interesting to note that the Rhône delta brackish environments are characterized by *Ammonia beccarii*, *Trochammina inflata* *Nonion depressulus* (this is more likely *Protelphidium anglicum*) and *Haplophragmoides canariensis* var. *provencensis*. Apart from the last named, these are all common to the Ebro delta brackish environments as well. *Ammonia beccarii* is also dominant in the Golfe de Fos which is equivalent to the Ebro lagoons. Kruit also distinguished an inshore assemblage with "Species whose distribution is restricted to the zone where transport is active". Among the species typical of this assemblage, the following also occur in the equivalent inshore assemblage of the Ebro delta: *Nonion asterizans*, *Eponides granulata*, *Triloculina* sp. and *Quinqueloculina rugosa*. He also distinguished a further assemblage which is characteristic of quiet water conditions off the Rhône delta; the species in common with the Ebro delta are: *Saccammina difflugiformis*, *Textularia calva*, *Eggerella scabra*, *Quinqueloculina longirostra*, *Pyrgo inornata*, *Valvulineria complanata* and *Elphidium lidoense*. The author's own samples from the Rhône delta have produced foraminiferids with many more species in common with the Ebro delta than Kruit's work reveals. The Rhône delta, although slightly larger, is similar in many respects to the Ebro delta, and this, together with their geographical proximity, has resulted in very similar foraminiferal faunas.

The Mississippi delta, on the other hand, is an entirely different type of delta; it is many times larger than the Ebro delta and is of the 'bird's foot' type. Even so, there are a surprising number of similarities of the foraminiferal assemblages compared with the Ebro assemblages. Lankford (1959) distinguished a marsh fauna with exclusively arenaceous species, including *Miliammina fusca* and *Jadammina macrescens*, and although his interdistributary bay environment has no exact parallel in the Ebro delta, its brackish nature gives it a foraminiferal fauna very similar to that of the Ebro brackish lakes, with *Ammonia beccarii* and *Elphidium gunteri* (probably synonymous with *E. oceanense*) common. Lankford also listed a deltaic marine assemblage whose boundary coincides with the "Overlap of rapid sedimentation with normal gulf water"; the following four species commonly constitute more than 90 % of the fauna: *Buliminella* c.f. *B. bassendorfensis*, *Bolivina lowmani*, *Nonionella opima* and *Epistominella vitrea*. *B. lowmani* is very similar to *Brizalina pseudopunctata* while

Table 2: Summary of the Ebro delta living foraminiferid assemblages.

Assemblage	Marsh	Lacustrine		Lagoon	Transitional	Inshore	Offshore	Deltaic marine
		Freshwater	Brackish					
Mean number of species/sample	2	1	3	17	23	19	36	24
Dominant species	*Jadammina macrescens* *Miliammina fusca*	*Protelphidium anglicum*	*Ammonia beccarii* *Elphidium oceanense* *P. anglicum*	*A. beccarii* *Brizalina striatula* *B. pseudopunctata* *Hopkinsina pacifica/atlantica* *Nonionella opima* Miliolids	*B. pseudopunctata* *N. opima* *H. pacifica/atlantica* *Rosalina valvulata* *Quinqueloculina schlumbergeri* *Asterigerinata* sp.	*Q. schlumbergeri* *Asterigerinata* sp. *Eponides granulata* *Nonion depressulus* *A. beccarii*	*N. opima* *B. pseudopunctata* *Bulimina aculeata* *Valvulineria complanata*	*B. aculeata* *V. complanata* *N. opima* *Epistominella vitrea* *A. beccarii*
Nature of boundaries	Physiographic	Physiographic		Physiographic, but gradational at seaward end.	Gradational; is area of convergence of inshore, offshore and lagoonal assemblages.	Coastline on landward side, grades into offshore assemblage on seaward side.	Gradational on landward side, from a depth of 9 - 16 m. to ?	Gradational; bordered by the inshore and offshore assemblages.
Remarks					Several offshore species occur in the shallow water, sheltered conditions in which this assemblage exists.	Coincides approx. with the delta front platform sedimentary environment, or the area of nearshore turbulence.	Coincides approx. with the pro delta slope sedimentary environment.	This assemblage is typical of the area of active sedimentation directly off the river mouth.

N. opima and E. vitrea are also very common in the Ebro deltaic marine assemblage. Finally, Lankford's Sound fauna occurs in conditions very similar to the Ebro lagoons and bears certain resemblances to the lagoonal assemblage, notably in the great abundance of Ammonia beccarii and miliolids.

STANDING CROP

The term 'standing crop' or 'standing stock' refers to the quantity of living organisms in a given area at a given time. It can be expressed in a number of ways involving the absolute numbers of organisms, their live weight (biomass), their displacement volume, their calculated volume, etc. To date, standing crops of foraminiferids have usually referred to the absolute numbers of foraminiferids per unit sample.

Standing crops of foraminiferids around the Ebro delta have been measured in two ways, in terms of absolute numbers of individuals per unit sample (equivalent to 50 sq. cm. surface area of sediment) and also in terms of the total calculated volume of foraminiferids per sample.

Standing crop in absolute numbers

Contoured standing crop values are illustrated in figure 40 and mean values for each assemblage are drawn up in Table 3. Standing crops vary overall from 7 - 1628 individuals per sample

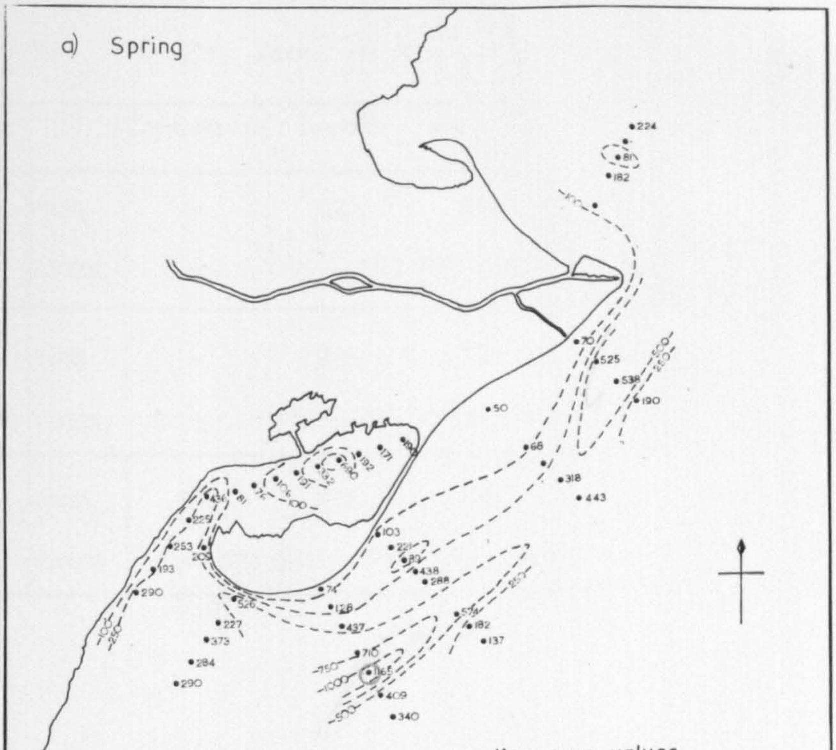
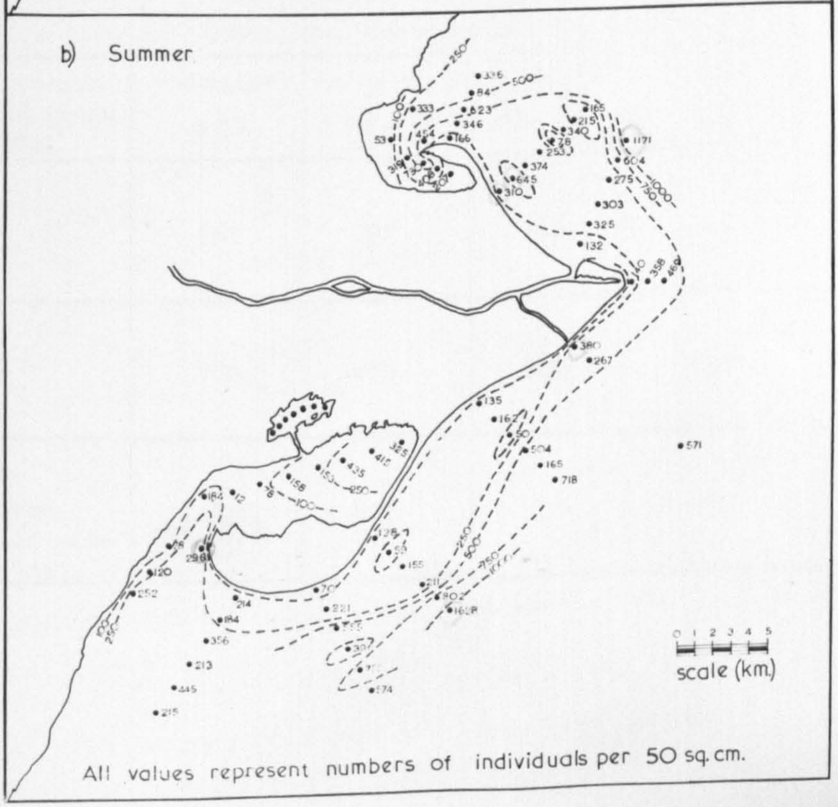


Fig. 40. Contoured standing crop values.



All values represent numbers of individuals per 50 sq. cm.

Table 3: Standing crop in the assemblages (nos. individuals / sampl

		Lacustrine	Lagoon	Transitio	Deltaic marine	Inshore	Offshore
Spring	mean	-	222 3	279	162 2	148 1	414 4
	range	-	81 - 690	193 - 436	81 - 224	50 - 526	137 - 1165
Summer	mean	-	225 2	186	468 3	182 1	532 4
	range	-	12 - 435	78 - 184	132 -1171	58 - 380	165 - 1628
Summer (S/ survey, northern side)	mean	236	416 3	280	-	314 1	285 4
	range	7 - 394	207 - 730	53 - 454	-	78 - 645	165 - 623

Table 4: Standing crop in the different sediment grades. (Mean no. individuals per sample).

% of sand grade material	'sand' >80	'muddy sand' 50 - 80	'sandy mud' 10 - 50	'mud' <10	All samples
Spring	1 233	3 291	2 251	4 337	289
Summer	1 170	2 179	3 420	4 437	349
Summer (S/ survey, northern side of delta).	3 330	4 587	1 207	2 259	318

and the mean value for all samples is 309.

In the spring, the mean standing crop per sample is 289. In general values increase gradually away from the shore, but there is an area in the 25 - 35 m. depth range southeast of the southern spit where maximum values are attained and deeper than this standing crop falls off slightly. Off the delta flanks there is a marked difference between the mean standing crop values of the inshore and offshore assemblages, 148 and 414 respectively. Values in the southern lagoon are relatively low, but there is a high in the central area with one value exceeding 500. Although the traverse was not complete, standing crops off the river mouth are low, ranging from 81 - 215. The relationship between standing crop and sediment grade is not clear cut, but generally the muddy sediments have higher values than sandy ones (see Table 4).

In the summer the general trend of increasing standing crop with increasing depth is still evident but the overall mean value has considerably increased over that of the spring, being 349. One of the most notable changes is in the marked increase of standing crop off the river mouth. One value exceeds 1000 and the mean of 468 for the deltaic marine assemblage is more than double that of the spring. The area of maximum standing crop remains in the same position as in spring, southeast of the southern spit, and the contrast between inshore and offshore assemblages is still apparent with mean values of 182 and 532 respectively. Lagoon standing crops are still relatively low but the area of highest values has shifted from the central area to the northeastern end. The relationship between standing crop and sediment type is more apparent with a great contrast between the mean values for sandy and muddy sediments (Table 4).

Off the northern side of the delta the overall mean value of standing crop differs only slightly from that for the summer in the southern part. In general, however, standing crops do not follow the same trends that are exhibited off the southern delta flank. Inshore and offshore assemblages are still distinguishable but the former has the higher mean standing crop. The delta front platform on this side of the delta has much higher values than the equivalent area to the south; a value of 645 is recorded relatively close to the shore at station S/10. This 'reversal' is reflected in the relation of standing crop to sediment grade; sandy sediments have a higher mean standing crop than muddy ones. The northern lagoon has much higher values than the southern side, and the highest standing crop of the S/ survey, 730, is recorded there. Encanizada has standing crops ranging from 7 - 394 with a mean of 236, very close to the summer mean (225) for the adjacent lagoon.

Discussion:

Standing crop measurements have frequently been taken as a reflection of the fertility (i.e. availability of nutrients) of the environment: thus a high standing crop would mean a fertile environment with plenty of nutrients available. Although this assumption may be correct in some cases, it is likely that many other factors are involved and these must be considered before standing crop can be taken as significant. All factors that influence standing crop are impossible to assess, but some explantions for the variation in values around the Ebro delta are attempted and the fertility of the different envirorments estimated.

It has to be established first of all that foraminiferids do respond to variations in the fertility of the environment. Bradshaw (1955) showed that, in laboratory cultures, the foraminiferid population (standing crop) increased when the supply of food (fertility of the environment) increased provided that physical conditions remained the same. Other laboratory studies, including Bradshaw (1961), have confirmed this. Lee et al. (1966) stated that both laboratory and field evidence suggests that many littoral foraminiferids are bloom feeders, and they add "When low concentrations of mature food organisms are present the Foraminifera eat and reproduce slowly; when large quantities of the appropriate food organisms are present in the form of a vigorously reproducing bloom, the Foraminifera may exploit this".

The nature of the food consumed by foraminiferids is important. Sandon (1932) concluded that the food is predominantly algal and species are basically unselective in what they accept as food. Lee et al. (1966) on the other hand, observed a considerable degree of selectivity amongst species they tested in the laboratory. Some species preferred a particular species of diatom and most yeasts, blue - green algae, dinoflagellates, chrysomonads and bacteria were rejected. Many workers, including Arnold (1954) and Lee et al. (1966), have observed that exceedingly high concentrations of living diatoms and/or green flagellates may depress foraminiferal populations. Arnold attributed this to chemical effects associated with excessive algal growth.

Several authors in the course of ecological studies on benthic foraminiferids have correlated high standing crops with diatom blooms, but it is necessary here to distinguish between benthic diatoms and those living within the phytoplankton. Lee et al. have established that foraminiferids will preferentially consume living benthic diatoms, but it is not known whether they will accept dead species being contributed to the sediment from the phytoplankton. Walton (1955), examining the foraminiferids of Todos Santos Bay, Baja California, considered that the June and August standing crop maxima reflect the peaks of phytoplankton production in the late spring and summer.

Vives and Planes (1952) examined the phytoplankton cycle in

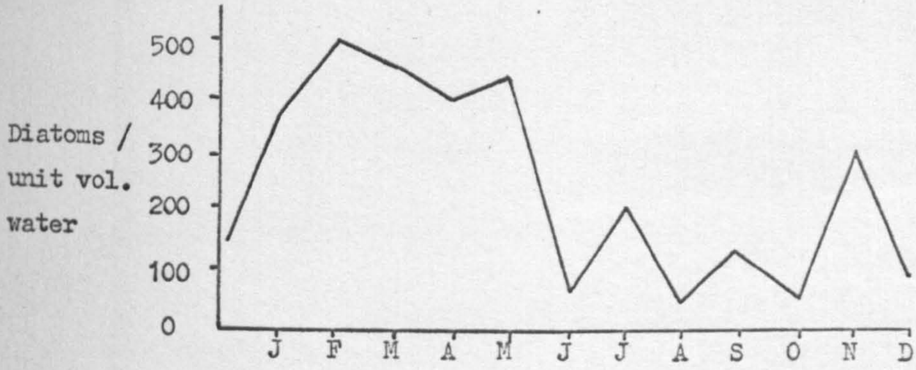


Figure 41: Annual cycle of phytoplankton off the Ebro delta (from Vives and Planes 1952).

the nearshore waters of the Ebro delta area and drew up an annual cycle (see figure 41 above). There is a distinct spring (January - May) maximum and diatoms are least abundant in the summer from June to October. This does correlate with the standing crop results, and it is likely that in the Ebro delta at least, the abundance of phytoplankton has no obvious influence on standing crop of foraminiferids.

The area directly off a river mouth has long been considered to be very fertile; rivers bring down great quantities of inorganic materials in solution which are used as food by primary producers. These in turn provide abundant food for other animals in the food chain. Phleger (1955), referring to the Mississippi delta, considered that the river brings down a great deal of plant nutrients and silica that encourage prolific diatom growth. This in turn supports high standing crops of foraminiferids. Lankford (1959) drew the same conclusions and stated "There are concentrations of nutrients and trace elements from soils in the Mississippi drainage area; large bacterial populations adhering to the surfaces of finely divided detritus which may be used as food; and organic solids". It is very likely that there is relatively high fertility off the mouth of the Ebro, but although summer standing crops are quite high, spring values certainly do not reflect this fertility.

Off the southern delta flank standing crops increase with depth but it is unlikely that depth of water itself has anything to do with the increase. Fertility, in terms of availablity of food, is unlikely to change much from nearshore to deeper water and it is more probable that the low standing crops in the inshore assemblage are due to the turbulent conditions over the delta front platform. The strong longshore currents make the environment unsuitable for many species. Sandy substrates are typical of the area occupied by the inshore assemblage and these may contain less finely divided organic material and fewer diatoms than muddy sediments which again would not encourage large standing crops. Elsewhere in the deltaic area, high standing crops have been recorded nearshore confirming that turbulence is probably the primary factor causing low standing crop in the inshore zone. There is no obvious reason why the area southeast of the southern spit should have the highest standing crops; obviously environmental conditions are particularly favourable for the species living there, but these same conditions are found elsewhere as well.

The northern side of the delta does not conform to the same pattern as the southern side; the inshore assemblage generally has higher values than the offshore assemblage. This may well be because of relative increase in fertility of the seawater because of the influence of the river discharging to the north. In addition, from observations in the field, it is known that this side of the delta is less subject to turbulence than the southern side, particularly in summer. It is sheltered from the strong south-easterly winds that develop during most summer days, and the river discharge may in some way ameliorate the effects of the longshore currents coming down the coast from the north.

Standing crops are relatively low in the southern lagoon. However, the abundant growths of weed in parts of the lagoon encourage animal life and relatively higher production of foraminiferids might be expected in this subenvironment. Low standing crops in the sediment may be caused by the high level of the oxidation/reduction line. Poor water circulation in the lagoon plus decay of organic material contributed from the weed tend to make the substrate reducing in nature. The reducing environment is almost certainly unsuitable for the majority of benthic foraminiferid species and therefore most will live within, or on the surface of, the oxidized portion of the sediment. At all stations the depth of the oxidation/reduction level in the sediment is less than 1 cm. and the thinness of this may restrict the size of the standing crops, although there are doubtless several other factors involved. Standing crops towards the western end of the lagoon are particularly low, but the reasons for this are unknown. It was observed that the sediment in this area is particularly thick and sticky and it may be unsuitable for living foraminiferids. This may possibly be due to some kind of pollution from San Carlos harbour although Bandy et al. (1965) recorded increased standing crops in polluted areas around ocean sewer outlets off the coast of California.

The reasons for the northern lagoon having larger standing crops than the southern lagoon may be due to a higher fertility there because of the influence of the river discharging on the northern side of the delta. Encanizada has standing crops approximately the same as the southern lagoon but differs in that the population consists almost entirely of one species, Protelphidium anglicum. The freshwater conditions and the poor water circulation limit the species that can live there and P. anglicum flourishes without competition.

The general increase of standing crop from spring to summer does not necessarily mean greater food availability in the summer. As maximum discharge of the river is in spring there is probably more food available then. The abundance of phytoplankton (figure 41) would confirm this. It is probable that temperature is very important. Several laboratory studies, including those by Bradshaw 1955, 1961, have demonstrated that most species have an optimum temperature for reproduction and it is likely that as summer approaches more and more species begin to reproduce. The level of fertility, although probably lower than the spring, is still sufficient to support large standing crops. Relatively rapid reproduction continues through the summer and results in a gradual build up of standing crop with a maximum probably in late summer.

Comparisons:

Several studies have been published which include standing crop data, but the majority of these concern areas along the coasts of the U.S.A. Other data is available from the coasts of Canada and Argentina. Only one other delta, the Mississippi delta, has been studied for its living foraminiferids (Phleger, 1955, Lankford, 1959) and this has been chosen for a close comparison with the Ebro delta results.

It must be remembered during this comparison that the Mississippi delta is altogether a larger delta than the Ebro delta as well as being of a different type. The discharge from the river is many times greater, and unlike the Ebro delta, seaward acretion is completely dominant over forces of marine erosion. All standing crop values from the Mississippi delta studies relate to a standard sample of 10 cm.^{2} and so they have been multiplied by 5 to give tentative direct comparisons with the Ebro delta values. Mississippi delta standing crop values, together with data from other published studies, is summarized in Table 5.

Lankford recorded standing crops of 10,000 - 125,000 in the deltaic marine fauna off the eastern Mississippi delta margin with a mean of 15,500. This is 50 times greater than the mean for the Ebro delta deltaic marine assemblage. Standing crops in the Mississippi delta marsh, interdistributary bay and fluvial marine environments were far more variable, with values from 33 - 3,500. Lankford's 'sound facies', approximately equivalent to the Ebro lagoon environment, has a mean standing crop of 615, three times greater than the Ebro lagoons. The open shelf facies, with a mean of 293, compares more closely with the Ebro inshore and offshore assemblages which have mean values of 206 and 443 respectively.

The waters of the main passes of the Mississippi delta have long been known to be extremely fertile with high organic production rates (in terms of organic carbon fixation rates) recorded where there are large foraminiferid standing crops. The water off the Ebro delta must be comparatively less fertile as standing crops never approach the size of those off the Mississippi delta. Margalef and Herrera (1964), in a study of the waters off the Catalan coast, stated that although detritus is always in high proportion around the Ebro delta, fertility is low. Their observations agree with what can be inferred by comaprison with the Mississippi delta. It appears that the River Ebro is not large enough to have significant influence on the fertility of the waters around its delta. Standing crops are probably little increased from those that would occur off an adjacent piece of non - deltaic coastline.

Standing crops recorded by Uchio (1960) off the Californian coast are considerably higher than those of the Ebro delta (see

Table 5: Comparison of Ebro delta standing crops with those from other areas.

Location and author	Assemblages				
	FW lacustrine	Lagoon	'Inshore'	'Offshore'	Deltaic marine
Ebro delta (both seasons)	m. 236 r. 7 - 394	262 12 - 730 (normal marine)	206 50 - 645	443 137 - 1628	366 81 - 1171
Mississippi delta (Lankford 1959)	Interdistributary Bay m. 1814 r. 180 - 3,505	Sound 615 65 - 3,455	Open shelf 293 220 - 365		Deltaic marine 15,500 10,000 - 125000
Lagoa dos Patos, Brazil (Closs 1963)		hyposaline lagoon r. <100 - >500			
Tracadie Bay, Prince Edward Is, Canada (Bartlett 1965)		hyposaline lagoon r. 5 - 360			
Laguna Guerrero Negro, Baja California (Phleger & Ewing 1962)		normal marine lagoon r. 300 - 3,890			
Laguna Madre, Texas (Phleger 1960a)		hypersaline lagoon north, m. 1000 r. 50 - 4,520 south, m. 4000 r. 0 - 12,400			
Shelf off California (Uchio 1960)			<24 m. depth zone m. 1,040 r. 660 - 1,415	24 - 82 m. depth zone 2,400 395 - 9,660	
Shelf off Long Island Murray 1969			37 - 69m. depth m. 234 r. 54 - 473		

m = mean, r = range; all numerical values relate to a sample of 50 sq.cm. surface area.

Table 5), but those recorded by Murray (1969) from a traverse off Long Island are much closer. Murray (1968) has summarized standing crop data for lagoons in various parts of the world, and many of these have similar values to the Ebro lagoons, although the only other normal marine lagoons studied, Phleger and Ewing (1962) - Laguna Guerrero Negro, Baja California, have considerably higher standing crops than the Ebro delta, ranging from 300 - 3,890.

Standing crop in calculated volume

The only published studies in which this measure has been used are those of Murray (1968, 1969). He refers to his results as 'biomass', but it is thought that this may be a little misleading as biomass is conventionally taken as meaning live weight. Ebro delta results are therefore referred to as 'calculated volume'.

The volume of foraminiferids was obtained by measuring the majority of the species under the microscope using an eyepiece micrometer. About 50 specimens each of the most abundant species were picked out and measured and the measurements used to calculate the average size of each species at each station. The volume of the average specimen was then calculated by referring its shape to one of the following geometrical shapes:

1. Cone, volume $\pi/_3\, r^2h$.
2. Oblate spheroid, volume $4/_3\,\pi a^2b$.
3. Prolate spheroid, volume $4/_3\,\pi ab^2$.
4. Cylinder, volume πr^2h.
5. Sphere, volume $4/_3\,\pi r^3$.

where a and b are major and minor radii respectively.

The calculated volume was multiplied by the number of individuals of that species recorded at a particular station to give the total volume for the species. For the less abundant species, the volume was calculated in one of two ways. Firstly, if the species was small, the volume was estimated, and secondly, if the species was larger, an 'averaged sized' individual was picked out, measured and its volume calculated. Finally, all the separate species volumes were summed to give the total volume for each sample.

A number of errors were involved in the calculation:

1. Errors in the actual measuring of specimens. These are thought to be very small and have been ignored.
2. The selection of an 'average sized' specimen can introduce errors. However, it was found that the accuracy of this method was not far off that obtained by measuring a large number of specimens and calculating a mean size, but the small loss in accuracy was amply compensated by the saving in time.
3. Foraminiferid tests are only approximately the same as the geometrical forms from which their volumes have been calculated and another small error may occur here.
4. Estimation of the volume of the smaller species may be wrong by several factors. However, their volume is so small as to make very little difference to the total volume and the error can be ignored.
5. Calculated volume should strictly refer to the total volume of foraminiferal protoplasm and in the calculations it is assumed that the total volume of the test of a specimen is more or less the same as the volume of protoplasm. Examination of the staining effects of rose Bengal shows that the majority of species stain all over indicating that the test is full of protoplasm. However, in some species, notably <u>Ammonia beccarii</u>, only the last few chambers are stained, which may indicate that the volume of the test is not a true measure of the volume of protoplasm.

It is difficult to assess how large these errors are; Murray (1968) suggested that they may be in the region of ± 20 %, but they are certainly not large enough to warrant abandonment of this method of representation of standing crop.

The purpose of determining the volumes of foraminiferids at the stations around the Ebro delta was firstly to see if the results had any meaning in themselves, and secondly to compare them with the standing crops in absolute numbers; i.e. to see if there was any significant difference between a sample with a small standing crop of large individuals and a sample with a large standing crop of small individuals. It may well be that calculated volume is a better reflection of the fertility of the environment that the number of individuals in a sample. Not every station was used for calculated volume measurements; those chosen were in most cases those that could be used directly for seasonal comparisons.

Calculated volume results are illustrated in figure 42 and the mean values for the different assemblages illustrated in Tables 6 and 7. In the spring the total of 29 samples chosen for calculated volume measurements produced totals ranging from 0.055 - 4.422 cu. mm. per sample, with an overall mean value of 1.209. The lowest values are recorded in the inshore assemblage on the delta front platform and volumes generally increase offshore although at the last few stations on the Salinas and Punta Bana traverses the values fall off again slightly. Station SP/28 has the highest spring value of 4.422 and the offshore assemblage has the highest mean value of 1.870. In the southern lagoon the mean calculated volume is 0.618 and values increase from the San Carlos end to the northeastern corner. Muddy sediments generally have higher calculated volumes than sandy sediments (table 7).

In the summer there is a wider range of calculated volumes, from 0.021 - 7.035, and the overall mean of 1.647 is slightly higher than that of the spring. Again, lowest values are recorded

Table 6: Mean calculated volumes for the assemblages (cu. mm./sample)

	FW Lacustrine	Lagoon	Transition	Deltaic marine	Inshore	Offshore
Spring	–	1 0.618		3 1.760	2 0.219	4 1.870
Summer	–	2 0.667		3 1.013	1 0.527	4 4.102
Summer (S/ survey, northern side).	1.977	4 2.065		–	1 0.678	2 0.997

Table 7: Mean calculated volume in the different sediment grades.
(cu. mm./sample)

% of sand grade material	'sand' > 80	'muddy sand' 50 – 80	'sandy mud' 10 – 50	'mud' <10	All samples
Spring	3 1.141	1 0.332	2 0.727	4 1.738	1 .209
Summer	2 0.899	1 0.574	4 2.098	3 1.740	1.647
Summer (S/ survey, northern side of delta)	1 0.710	3 1.378	4 2.752	2 1.147	1.157

a) Spring

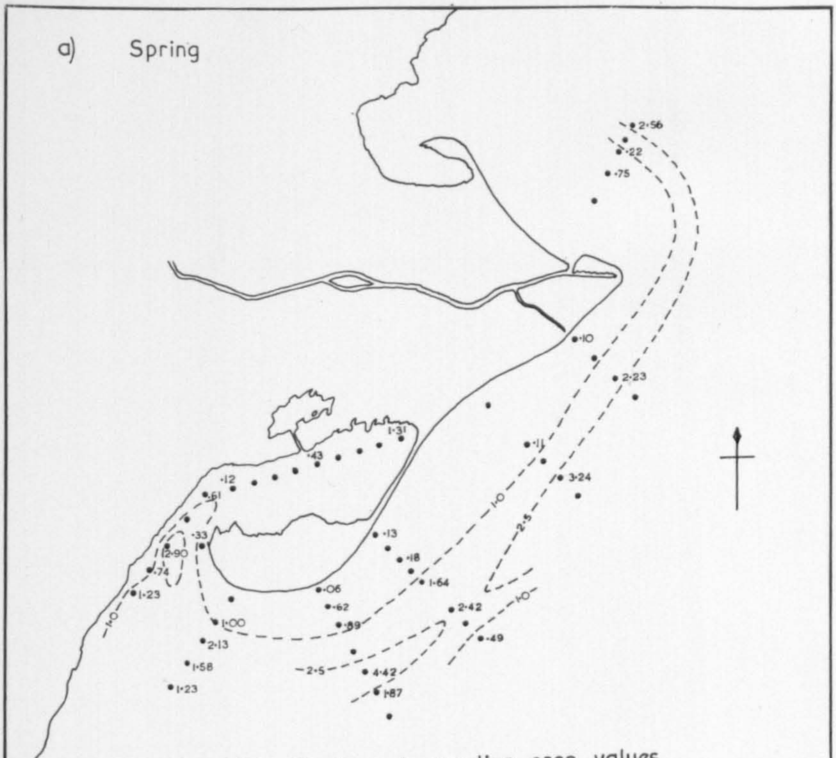
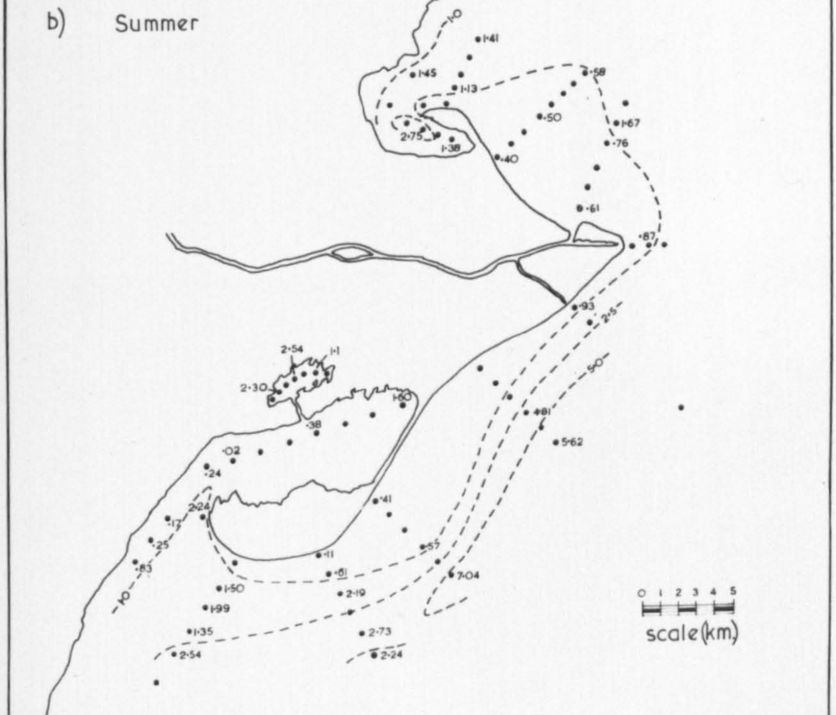


Fig. 42. Contoured standing crop values

b) Summer



All values in cu. mm. per 50 sq. cm.

in the inshore assemblage and highest values in the offshore assemblage; respective mean values are 0.527 and 4.102. As in spring, values increase gradually with depth until the deeper water stations when there is a slight decrease. There is a distinct region of maximum calculated volume (more than 5.000 cu. mm. per sample) towards the edge of the delta front platform running parallel to the coast. The mean value for the southern lagoon is only slightly higher than that of the spring, being 0.667, and values again increase into the northeastern corner.

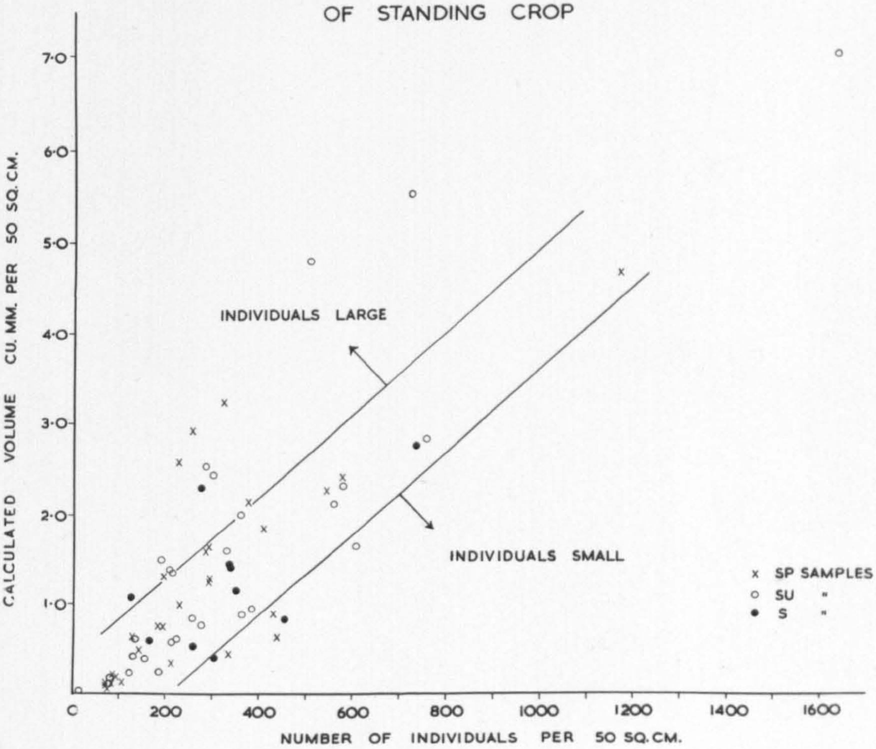
On the northern side of the delta calculated volumes range from 0.399 - 2.752. The contrast between inshore and offshore assemblages is not as marked as on the southern side but lagoon values are relatively high, ranging from 1.378 - 2.752. Values for the three stations in Encanizada are also relatively high, with a mean of 1.977.

Discussion:

The general distribution trends shown by calculated volumes are virtually the same as those shown by standing crop in absolute numbers. However, a plot of standing crop against calculated volume (figure 43) shows that the relationship between the two is far from steady and justifies their separate examination. For example, there are some samples which have only average sized standing crops but are composed of relatively large individuals and therefore have a high calculated volume.

As with absolute numbers, calculated volume values increase away from shore to a maximum in a depth range of 13 - 20 m. but deeper than this they fall off again slightly. Again the significance of this area of maximum values is not obvious but conditions must be especially favourable to allow such large standing crops to develop.

FIG. 43. RELATIONSHIP BETWEEN THE TWO MEASURES OF STANDING CROP



Turbulence rather than lower fertility is probably the cause of low calculated volumes in the inshore assemblage on the southern side of the delta. On the northern side the relatively high values in the same assemblage are probably due to higher fertility resulting from the river discharging on this side of the delta. This increased fertility is also reflected in the northern lagoon where calculated volumes are greater than those in the southern lagoon. The increase of values to the northeastern corner of the southern lagoon may be due to increasing fertility of the water; this in turn may be due to runoff from the delta via the numerous drainage channels. Higher calculated volumes in Encanizada possibly infer that fertility is higher there than the southern lagoon; plant and animal life was observed to be extremely abundant all over the lake.

In the deltaic marine assemblage, calculated volumes are low in relation to the numbers of individuals present in each sample. It could readily be observed that specimens of most species were slightly smaller than those from other environments. Bradshaw (1955) stated that in areas of active sedimentation where there is a fertile environment (as off a river mouth), individuals are smaller than their average size elsewhere because they are able to reproduce rapidly under favourable environmental conditions. Many are unable to attain full size before being buried by sediment. Lankford (1959) also reached this conclusion when seeking an explanation for small individuals off the main passes off the Mississippi delta. It seems therefore, that, in the case of river mouth areas, calculated volumes are not a good indication of fertility; they imply low fertility whereas the opposite is usually the case.

Calculated volume also follows the absolute numbers trend in having higher mean values in muddy sediments, but it is not known whether the sediment itself is most important or whether factors associated with it, such as food content, lack of turbulence, etc., have more significance. In both summer surveys the 'sandy mud' grade of sediment supports the highest mean calculated volumes and several authors, including Phleger (1960) and Boltovskoy (1965), have also observed that 'mixed' sediments support largest populations. On the southern side of the delta there is an overall increase in calculated volume from spring to summer following the trend of absolute numbers. The explanation for this is probably related to the absolute numbers in that more rapid reproduction through late spring and summer results in larger standing crops and hence larger calculated volumes.

Comparisons:

Murray has carried out similar studies on three areas along the eastern seaboard of the U.S.A. (1969) and in Buzzard's Bay (1968). His 'biomass' values related to samples representing 30 cm.^{2} surface area of sediment but have been corrected to the equivalent of 50 cm.^{2} for direct comparsion with the Ebro delta results. They are summarized below:

		Range		Mean
Buzzard's Bay	sand	0.6 - 2.6	2.2	1.45
	silt	0 - 0.9	0.55	
Vineyard Sound		0.333 - 1.730		0.690
Shelf off Long Island		0.015 - 3.120		1.542
Cape Lookout to Cape Hatteras		0.015 - 1.568		0.400

In Buzzard's Bay sandy sediments have a higher mean calculated volume than the silty sediments which is the opposite of the Ebro delta pattern. Comparisons are made more difficult by the environments being different, but there is a general trend in the bay of increase in 'biomass' from the inner end to the open sea, which is opposite to the southern lagoon trend.

Vineyard Sound has a mean calculated volume very close to that of the southern lagoon but again comparison is difficult because Vineyard Sound is a totally different environment with a rocky bottom in places, strong tidal currents, etc. The Cape Lookout - Cape Hatteras region has very low calculated volumes but Murray recorded higher values in the traverse off Long Island. The mean value here is comparable with values off the Ebro delta flanks. However, the Long Island traverse does not show a gradual increase in values with increased depth; Murray recorded fluctuations of 'biomass' near the coast and then fairly uniform values on the remainder of the traverse.

Conclusions:

In conclusion, it can be said that neither measure of standing crop is totally satisfactory for fertility assessment because both are influenced by other environmental factors besides the fertility of the water. In the absence of comprehensive information concerning the factors operating in an environment, standing crop can only be safely taken as indicative of fertility where values are extreme, very high values indicating a high fertility and low values indicating a relatively low fertility. Murray (1967) considered that areas of the sea floor having the equivalent of more than 5000 living individuals per 50 $cm.^2$ sample must be regarded as regions of high fertility, and that less than 50 individuals per sample indicates low fertility. Similarly, areas with a calculated volume of 5.0 cu. mm. per sample probably indicate high fertility, and less than 0.5 low fertility.

The indications are that the fertility of marine environments off the Ebro delta, with the exception of the area directly off the river mouth, is little different from an area off the non - deltaic coastline in the same area. River discharge is probably not sufficient to make any significant difference to the fertility of most of the surrounding water.

DIVERSITY

Introduction

Faunal diversity, or variability, has been defined by Walton (1964) as being based on the number of species of organisms that occurs in any given environment. Sanders (1968) pointed out that a search through the literature reveals two definitions resulting in some confusion. He distinguishes one kind of diversity as the numerical percentage composition of the various species present in the sample; the more the constituent species are represented by equal numbers of individuals the more diverse the fauna. The other kind of diversity is determined by the number of species in a sample, the more species the greater the diversity. Sanders suggests that this should be referred to as species diversity and considers that it is the more valid measurement of the two.

Measurement of diversity began when attempts were made to find mathematical formulae to fit observed frequency distributions. A great number of methods are now available to represent diversity including the use of 'diversity indices'.

Fisher, Corbett and Williams (1943) undertook an early examination of diversity and proposed an index of diversity which can be derived from the formula

$$\alpha = \frac{n_1}{x}$$

where x = a constant <1 and n_1 can be calculated from $N(1 - x)$ where N is the size of the population.

Part of Yule's (1944) statistical examination of the literary vocabulary was modified by Simpson (1949) for application to diversity. Gibson (1966) utilized Simpson's ideas in a study of diversity of benthic foraminiferids from the Mississippi Sound. He used a diversity index calculated from the formula:

$$\frac{N(N - 1)}{\begin{array}{l} Kn_i(n_i - 1) \\ \Sigma \\ i = 1 \end{array}}$$

where N = total number of individuals, K = number of species and n_i = number of individuals of the $_i$th species.

This index has the drawback that it puts greater significance on the more abundant species whereas the α index considers the rarer species as well. Williams (1964) considers that the α index is the more consistent measure where the population distributions are in log - series form. Several other diversity indices are in common use and Gibson (1966) notes that recently more use has been made of entropy. This and other refined sample distribution statistics have been used to measure the degree of uniformity in the distribution of a species within a population.

Many workers have utilized the logarithmic relationship that exists between the distribution and species and individuals within a community. Odum, Cantlon and Kornicker (1960) introduced a plot of the cumulative number of species from a sample against the logarithm of the number of individuals. The resulting 'cumulative' or 'diversity' curves have a gentle slope when diversity is low and a steep slope when it is high. Walton (1964) utilized this method but substituted percentage data for absolute numbers of individuals. Murray (1968) argued that this has the disadvantage of eliminating the effects of sample size, and unless the samples were all originally of the same number of individuals errors of interpretation may result.

In the present study, three methods of diversity measurement have been used:

1. Simple number of species per sample.
2. The α index of Fisher, Corbett and Williams.
3. Cumulative curves.

One of the fundamental drawbacks of most diversity measurements is that they are sample - size or density dependent. The usual difficulty in comparing samples of different sizes is that as the sample size increases, individuals are added at a constant arithmetic rate but species accumulate at a decreasing logarithmic rate. However, in the present study all samples are of unit size and diversity measurements can be safely compared. Sanders (1968) introduced a procedure of measurement, the 'rarefaction method', by diversity can be compared irrespective of sample size.

The three methods listed above were chosen because they were considered both valid and reasonably rapid methods. The number of species per sample can rapidly be assessed from the population data, while the α index can be quickly read off a standard plot (figure 44, adapted from figure 125, Williams, 1964). Murray (1968) considered that cumulative curves are convenient because they more readily portray diversity relationships at a glance than numerical indices. α indices can be read off from the same plot as the cumulative curves, but as Murray stresses, with the latter it is the position of the curve and the steepness of its slope that is important, whereas only the end point of the curve defines the α index. Cumulative curves have been used chiefly to define diversity fields into which samples from particular assemblages plot.

Results

The areal distribution of the number of species per sample is shown in figure 45 and the mean number of species for each

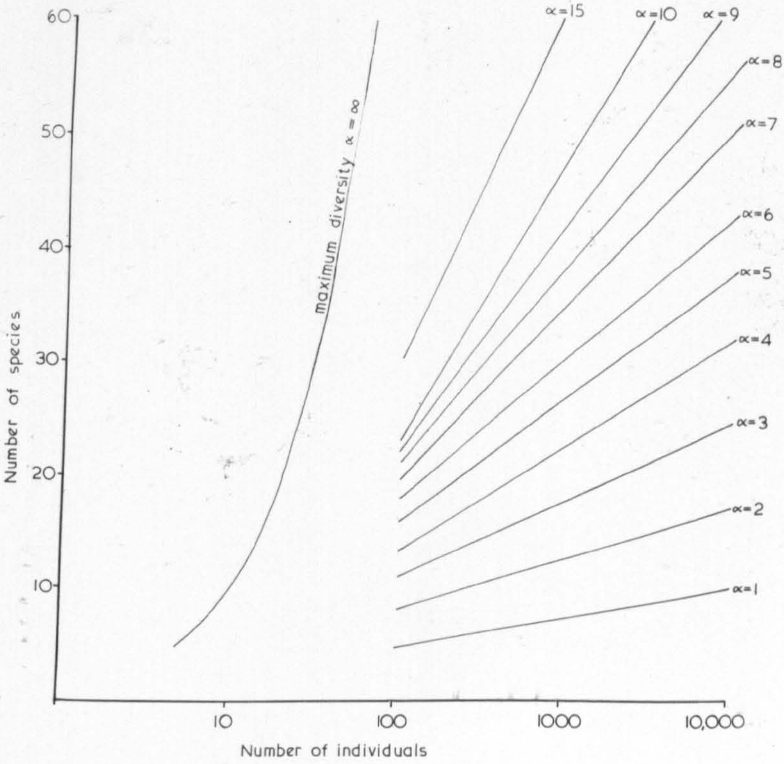
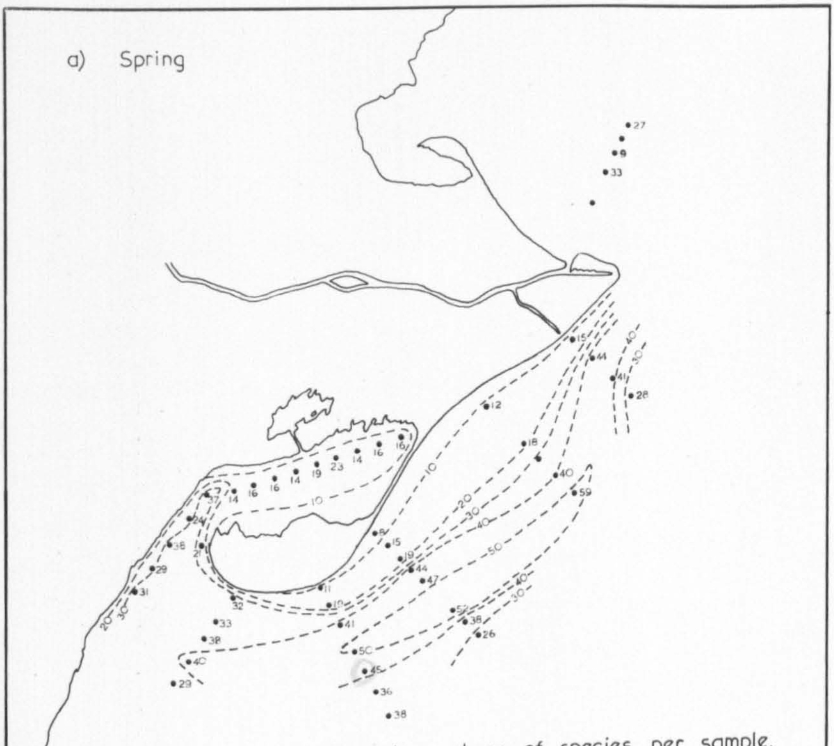
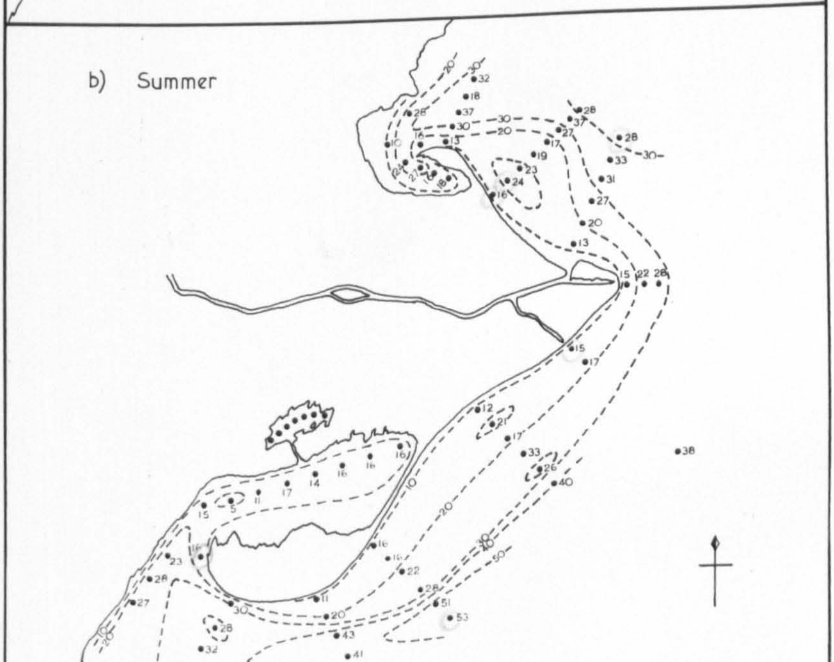


Fig.44. Plot for reading off α indices
(from Williams 1964)



a) Spring

Fig 45. Contoured numbers of species per sample.



b) Summer

assemblage are drawn up in table 8.

The mean number of species for all samples in the spring is 28. Off the southern delta flank there is an increase in the number of species with depth up to the 15 - 27 m. depth range where the highest numbers of more than 50 species per sample occur. With further increase in depth numbers fall off slightly to between 30 and 40. The offshore assemblage has a higher mean value than the inshore assemblage, 40 compared with 17. Only three samples were taken off the river mouth and one of these was not of adequate size and so the mean value of 23 for the deltaic marine area cannot be considered entirely reliable. The number of species in the southern lagoon is fairly steady, varying from 14 - 22 with highest numbers occurring in the central part of the lagoon. The mean value for the lagoon is 28, whereas the transition area has a surprisingly high mean of 28.

For the summer survey of the southern part of the delta the mean number of species is 25, slightly lower than the spring. Numbers off the southern delta flank follow the same pattern as in the spring although the tailing off seaward of the zone of highest numbers is less apparent because only on the Punta Bana traverse were the same depths reached as in spring. The area of highest number of species (over 50 per sample) is in approximately the same position as in spring but is less extensive. The 20 species per sample contour is closer to the shoreline than in spring and this is reflected in a slight increase in the mean value for the inshore assemblage. The offshore assemblage, however, has a slightly lower mean than the spring, 37 compared with 40. Off the river mouth there are increasing numbers of species with depth until the deepest sample when there is a slight decrease. This follows the pattern off the southern delta flank. The transition area again has high numbers of species in places but

TABLE 8 Diversity data

Survey	Assemblage	No. of samples	Mean no. of species	Range	Range of α indices	Mean α	
SP spring 1967	Lagoon	9	16	14 - 22	3.4 - 6.1	4.4	1
	Transition	6	28	21 - 38	6.7 - 10.5	8.7	4
	Inshore	9	17	11 - 32	2.0 - 7.4	5.0	2
	Offshore	19	40	26 - 59	7.9 - 11.7	11.5	5
	Deltaic marine	3	23	9 - 33	3.5 - 11.7	7.9	3
	All assemblages	46	28	9 - 59	3.5 - 11.7	8.3	
SU summer 1967	Lagoon	7	14	5 - 17	3.5 - 5.0	4.0	1
	Transition	5	22	15 - 28	3.8 - 12.2	7.7	4
	Inshore	15	19	11 - 30	3.1 - 9.8	5.4	2
	Offshore	17	37	27 - 53	6.2 - 11.8	9.1	5
	Deltaic marine	6	25	13 - 33	3.5 - 9.2	6.3	3
	All assemblages	50	25	5 - 53	3.1 - 12.2	6.8	
S summer 1968	FW lacustrine	7	2	1 - 3	-	<1.0	
	Lagoon	5	19	11 - 25	2.4 - 6.0	4.2	1
	Transition	3	18	10 - 28	3.2 - 7.2	4.6	2
	Inshore	8	21	13 - 30	3.8 - 7.8	5.7	3
	Offshore	5	30	18 - 37	6.8 - 13.0	9.4	5
	All assemblages	21	22	10 - 37	3.2 - 13.0	6.1	

(excl. FW lac.)

the mean value is less than that of the spring. The northeastern end of the lagoon has similar numbers of species as in spring, but numbers fall off towards San Carlos harbour and the summer mean for the lagoon is consequently a little lower than that of the spring.

In the summer survey of the northern side of the delta, the inshore assemblage has a lower mean number of species than the offshore assemblage, but this is a little higher than for the same area off the southern delta flank. The offshore assemblage mean is much lower than on the southern side of the delta but this may be because there were not so many stations in deeper water where it might be expected that larger numbers of species would occur. The northern lagoon, although much smaller than the southern one, supports a slightly more diverse population and the mean number of species is slightly higher than that of the southern lagoon. Encanizada has very low diversity; there are never more than three species in a sample and several samples produced only one species.

Areal plots of α indices are shown in figure 46 and the mean values for the various assemblages are drawn up in table 8. α indices also increase with depth up to approximately 20 m.; deeper than this they fall off slightly. The mean index for the inshore assemblage does not vary much in the three surveys but the ranges are somewhat more variable. The two summer surveys have very similar mean indices in the offshore assemblage, but the spring mean is noticeably higher. Deltaic marine assemblage indices are variable but are generally lower than for the equivalent depths off the delta flanks. In the lagoons α indices are similar for both seasons with mean values ranging from 4.0 - 4.4. The area of highest indices is virtually the same in spring and summer, southeast of the southern spit, although the highest indices in spring

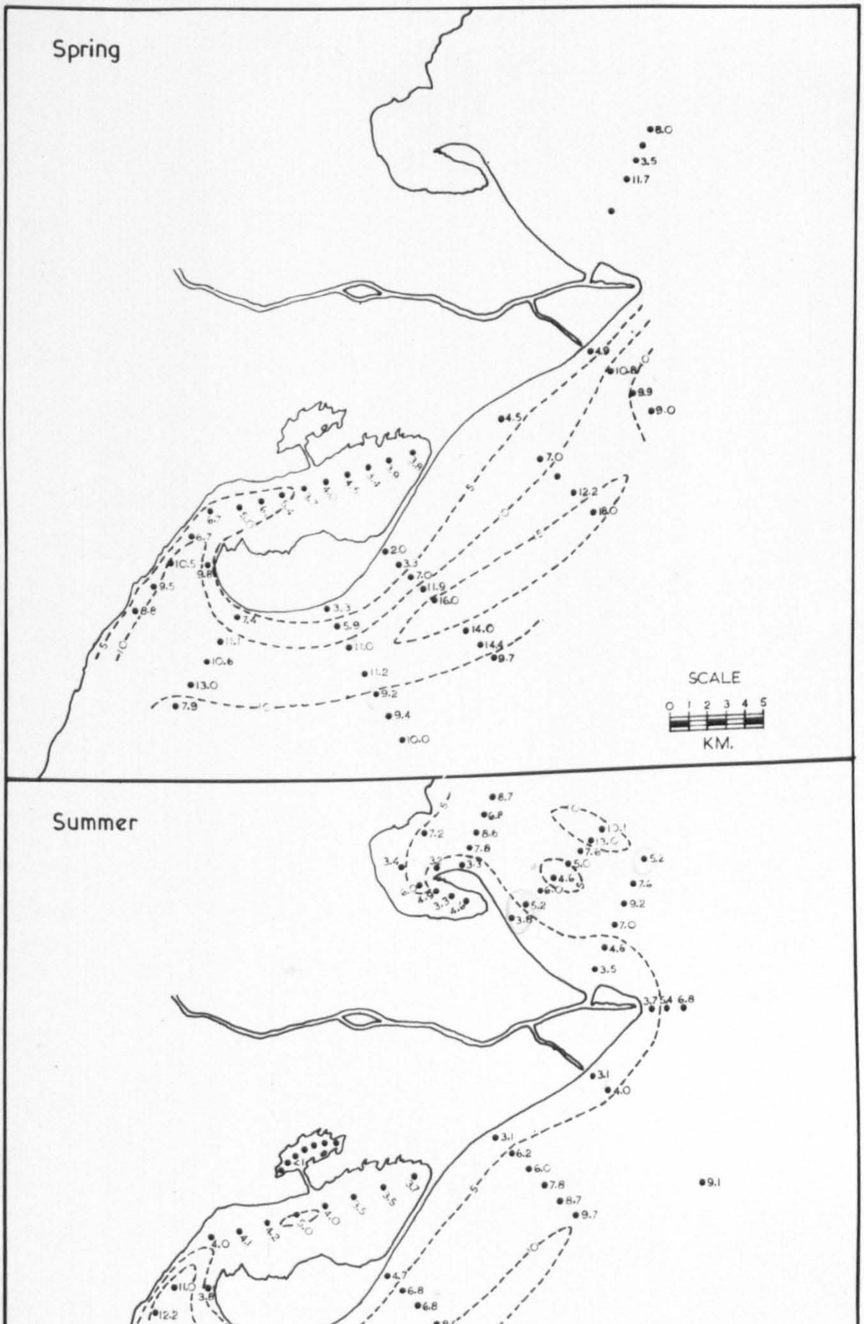


Fig. 46. Contoured α indices

are much higher than those of the summer.

The diversity fields of the different assemblages are shown in figure 47. The cumulative curves for stations from the offshore assemblage are very steep while those of the inshore assemblage are much flatter, indicating lower diversity. The deltaic marine and transition assemblage curves fall into an intermediate region between the inshore and offshore fields. The lagoon field also plots low, coinciding with the lower part of the inshore assemblage field. Encanizada (freshwater lake assemblage) has the most distinct diversity field, the small number of species results in it plotting very low.

Discussion

A plot of diversity values against depth (figure 48) shows a general increase away from shore. with depth. However, it is not considered that depth itself has any significance on species diversity in the relatively shallow water sampled. One of the most important aspects is the stability of the environment. Walton (1964) considered that the number of species of benthic foraminiferids is inversely proportional to the variability of the environment and Sanders (1968) proposed a 'theory of environmental stability' whereby the more stable the environmental parameters, such as temperature, salinity and oxygen, the more species present.

On this basis, the offshore assemblage, which has the highest diversity around the delta, occupies the most stable environment. This ties in well with environmental observations from various parts of the delta. The inshore assemblage on the delta front platform is subject of considerable turbulence and only beyond the wave base does diversity increase significantly. The significance

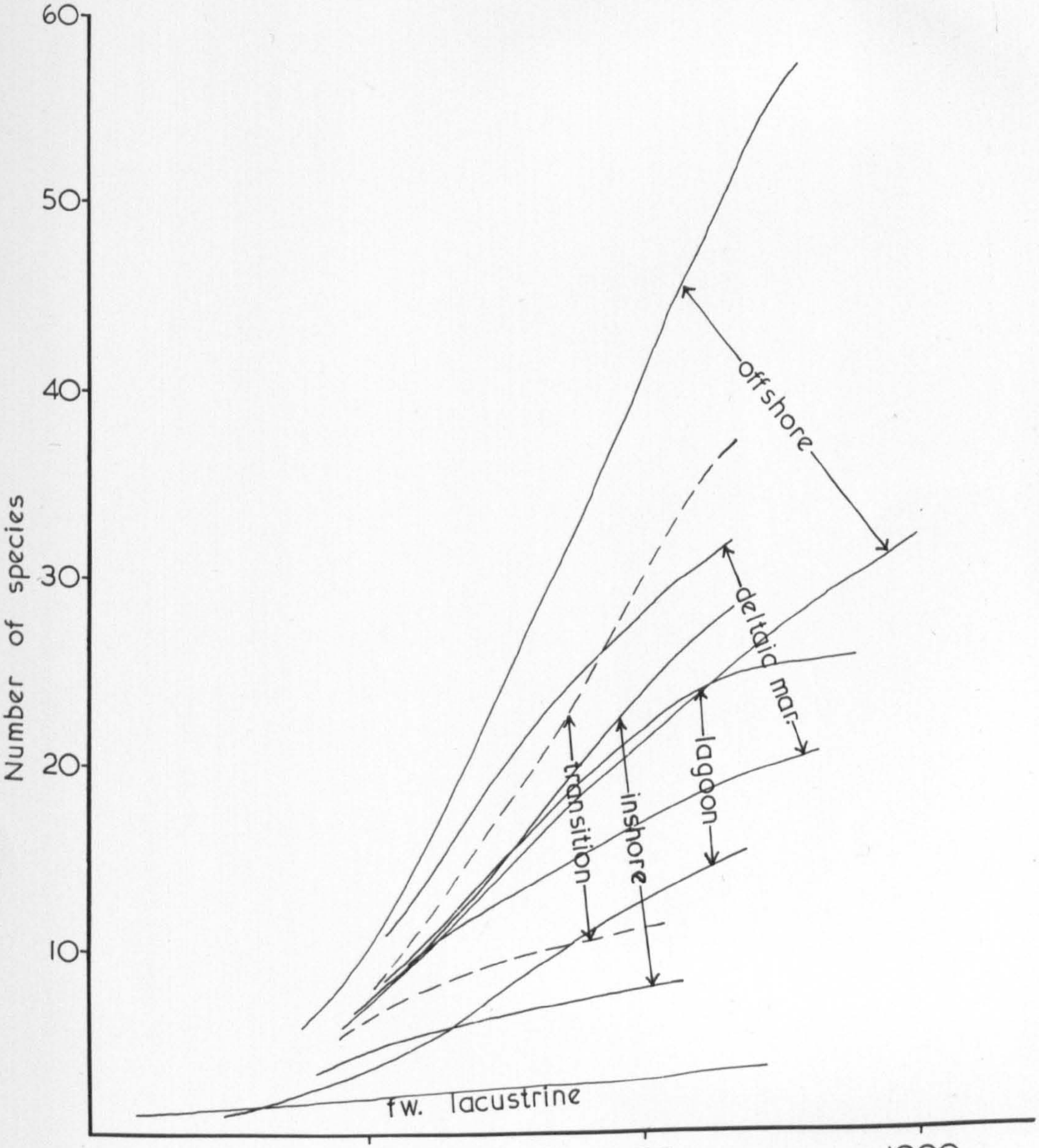


Fig. 47. Diversity fields into which cumulative curves from the different foraminiferal assemblages fall.

of the effects of turbulence is clearly illustrated by comparison of the diversity of the inshore and transition assemblages. The two assemblages inhabit similar depths and are similar distances from shore, yet the mean α indices, e.g. for spring, are 5.0 for the inshore and 8.7 for the transition assemblage. It is clear that the sheltered location of the transition area provides a more stable and less vigorous environment than the delta front platform.

It is not known what happens to diversity in water deeper than that sampled in the Ebro surveys. In the Gulf of Mexico, Walton (1964) considered that the maximum number of species occurs on the edge of the continental shelf. Bandy (1954) had recorded the same observation but Buzas and Gibson (1969) suggest that maximum species diversity occurs in abyssal depths greater than 2500 m. They examined dead foraminiferids in samples from the western North Atlantic and discovered two subsidiary diversity peaks, at 35 - 45 m. and at 100 - 200 m. However, the 35 - 45 m. peak was due to species equitability rather than a high number of species.

Diversity is lowest in the subaerial environments on the Ebro delta. Although quantitative samples are available only from Encanizada, there are rarely more than about 6 species in either marsh or lacustrine environments. This reflects the exceedingly unstable environmental conditions operating there; variations in salinity, pH, temperature etc. are common and extremes are frequently reached. Murray (1968) stated that two environmental characteristics seem particularly important in determining diversity in lagoons, the deviation of salinity from normal marine and the lithology of the substrate. Plots of the relation of sediment grade to diversity around the Ebro delta reveal no definite correlation and it is considered that the nature of the substrate

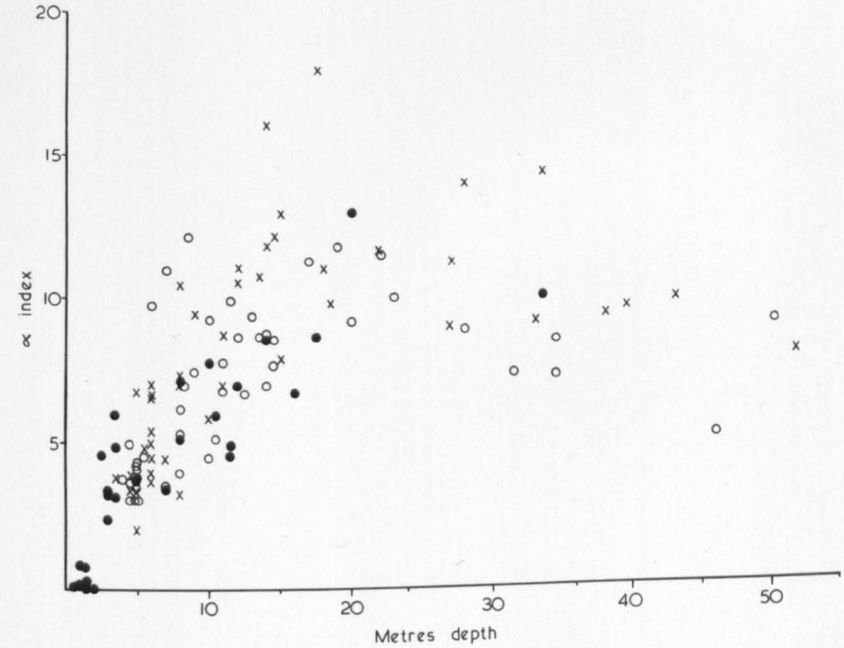


Fig. 48. Relationship between diversity and depth.

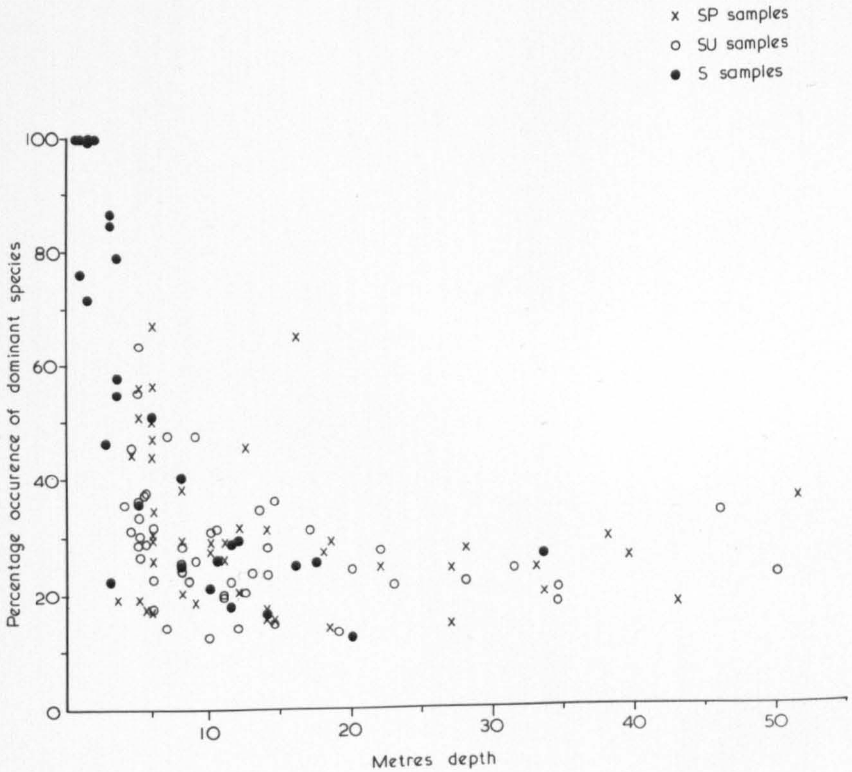


Fig. 49. Percentage occurence of dominant species in the living populations plotted against depth.

is relatively unimportant in this case. Salinity is consistently normal in both the Ebro lagoons and other environmental factors must be variable to account for the low diversity. Poor water circulation resulting in low oxygen availability may be one cause.

Sanders (1968) listed a number of other concepts related to diversity. He recorded that all communities tend to diversify with time so that older communities are more diverse than younger communities. The 'competition theory' states that in environments of high physiological stress natural selection is largely controlled by the physical variables. This ties in well with the concept of faunal dominance as introduced by Walton (1964). Associated with a decrease in diversity near to the shore as the environments become more unstable, there is a general increase in the relative abundance of the dominant species. Walton records that 100% of the faunas in the northeastern Gulf of Mexico whose dominant species constitutes over 35% of the entire population, occur shallower than 10 fathoms (approx. 19 m.). This relationship around the Ebro delta is plotted in figure 49; samples with very low diversity, such as those from Encanizada, usually have one species comprising the greater part of the fauna. Few species are adapted to the rigorous conditions of marginal marine conditions and so one well adapted species would easily be dominant. On the other hand, in the more favourable, stable environments that occur offshore, there are many more species and inter - specific competition correspondingly more intense. In this situation, a single species rarely achieves a significant high dominant percentage.

Another concept listed by Sanders is the 'productivity theory' which states that "All other things being equal, the greater the productivity the greater the diversity". Sanders, however, is dubious as to the validity of this theory. He suggested that it is conceivably correct, but under natural conditions it may be masked by numerous environmental variables. High productivity, from sheer amount of organic matter produced, can create severe stress conditions and low diversity and he quoted examples of some upwelling areas where high production is responsible for low oxygen content of the water on and just above the ocean floor. Similarly, the highly productive eutrophic lakes often have bottom water devoid of oxygen. This feature may also be illustrated off the Ebro delta where in the deltaic marine assemblage diversity is not as high as for equivalent depths off the delta flanks. This may be due to very high productivity, or alternatively, to the adverse effects of very rapid sedimentation.

Comparisons with other areas

In only a few published works on living foraminiferids has diversity been considered as a separate topic. In addition, most studies have used a smaller sample and so the Ebro results are not directly comparable, because, as as been mentioned earlier, diversity is dependent to a large extent on sample size. Nevertheless, some general comparisons can be made.

Data from Lankford (1959) and Walton (1964) from the Mississippi delta and the northeastern Gulf of Mexico has been examined and reinterpreted for comparison with diversity around the Ebro delta. Lankford records a total of 52 living species off the eastern margin of the Mississippi delta in depths from 1 - 35 m. This is much less than the total of 115 species from the Ebro delta in depths from 3 - 55m., but the deeper water samples and the larger size of the unit sample may account for this difference. Number of species per sample off the Mississippi delta varies from 1 - 29 and α indices range from $< 1.0 - 4.9$ (see table 8 for Ebro delta equivalent values). Despite the disparity in sample size, diversity must be considered as low off the Mississippi delta compared with the Ebro delta. Walton's contoured diagram showing numbers of species in the northeastern Gulf of Mexico brings out maximum numbers of 60 - 80 near the edge of the continental shelf, but much lower numbers in equivalent depths off the Mississippi delta. Therefore, applying the conclusion already drawn about diversity, it can be said that environments around the Mississippi delta must be relatively unstable. The numerous distributaries probably produce varying salinities in the adjacent marine areas associated with a known high rate of sedimentation. As diversity off the Ebro delta is relatively high it must be concluded that outflow from the River Ebro has very little influence on the surrounding marine areas and that a normal, stable marine environment exists in most places except close inshore. It must be remembered that diversity only reflects the variability of the environment and not its fertility, so although the stability of the Ebro delta offshore environments results in a higher diversity, the higher standing crops off the Mississippi delta probably reflect a much higher fertility there.

It would seem, therfore, that a relevant comparison for the Ebro delta would be with an ordinary non - deltaic coastal area. Murray (1969) produced some results from the Atlantic coast of the U.S.A. The traverse off Long Island produced 14 - 24 species per 30 $cm.^2$ sample and α indices ranging from 4 - 11. α indices up to 13.0 were recorded along the Cape Lookout to Cape Hatteras traverse but diversity values do not generally seem as high as those around the Ebro delta. Murray noted that most of his traverses support cold water assemblages and it is well known that diversity decreases in colder waters. Sanders (1968) noted that natural selection in the higher latitudes is controlled by the physical environment, while in low latitudes biological competition

TABLE 9

Station	212	213	214	215	216	217	218
Depth (metres)	18	15	31	40	33	27	18
Number of species	23	25	29	32	22	32	24
Standing crop	328	264	403	370	91	632	537
α index	5.6	6.6	7.0	8.4	9.7	7.0	5.2

Foraminiferal diversity of 7 samples (10 cm.^{2}) from a traverse across the northern Gulf of California (from Phleger 1964).

becomes paramount.

In Walton's (1955) samples from Todos Santos Bay, Baja California, there are rarely more than 20 species per sample (10 cm.^{2}) and α indices do not exceed 6.5. Again, these values seem comparatively low. Diversity is higher in the Gulf of California and Phleger (1964) recorded 20 - 30 species per sample (10 cm.^{2}) in equivalent depths to Ebro delta stations. Table 9 shows diversities calculated from part of Phleger's data for one traverse from coast to coast in reasonably shallow water. It can be seen that highest diversities are recorded in the middle stations (215, 216) of the traverse which are farthest away from the shorelines, following the Ebro delta pattern. Numbers of species and α indices are also closer to Ebro delta values.

Murray's data (1968) on lagoons indicates an α index range from 4 - 11 (per 10 cm.^{2} sample) for the few normal marine lagoons that have been studied to date. Bearing in mind that Ebro delta lagoon α indices of around 4.0 - 6.0 would probably have been higher had a smaller sample been used, there is fairly close similarity here. Normal marine lagoons appear to support more diverse populations than either hyposaline or hypersaline lagoons.

c) SPECIFIC ECOLOGY

Eggerella scabra (Williamson)

In the spring E. scabra is widespread throughout most environments but its relative abundance is generally low; at only one station does it exceed 5 %. In the summer there is little change in distribution. There are a few individuals at most stations but again only one value exceeds 5 % (figure 50). Figure 51 shows mean relative and absolute abundances for the different assemblages and it can be seen that they are generally very low; the northern lagoon stands out with the highest absolute abundance.

The sediment / abundance plot in figure 51 demonstrates that living E. scabra has no preference for a particular grade of substrate; it is found in practically all grades of sediment encountered. Similarly, it shows no depth preference in an overall range from 2½ to more than 53 m. There is no preferred seasonal abundance and the only ecological conclusions that can be drawn from its distribution around the Ebro delta are that it is tolerant of a wide range of sediment grades and depth ranges but is never found in conditions of sub - normal salinity.

The dead population stands out because of its considerably higher relative abundance compared to the living populations. In the southern lagoon where practically no living individuals were recorded there is up to 8% of E. scabra in the dead population. Highest abundance in the dead population occurs in an area stretching from the outer edge of the northern delta front platform (up to 20 m. depth) eastwards to include one station on the river mouth traverse. The reasons for high relative abundance in

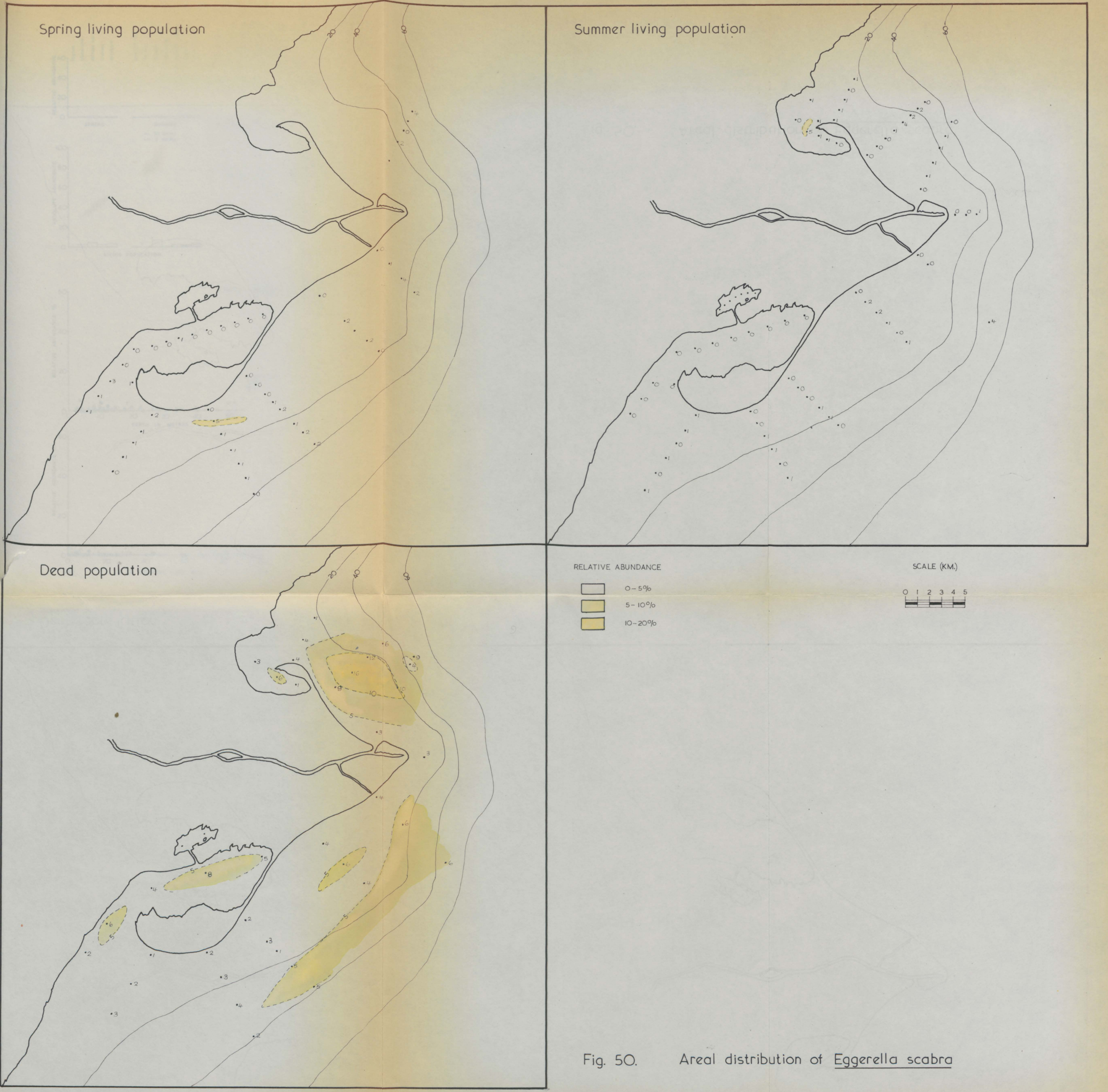
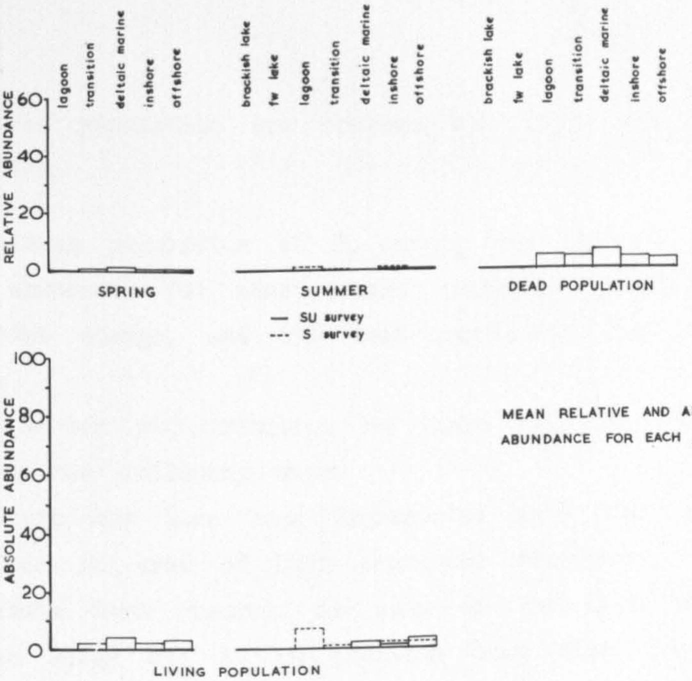
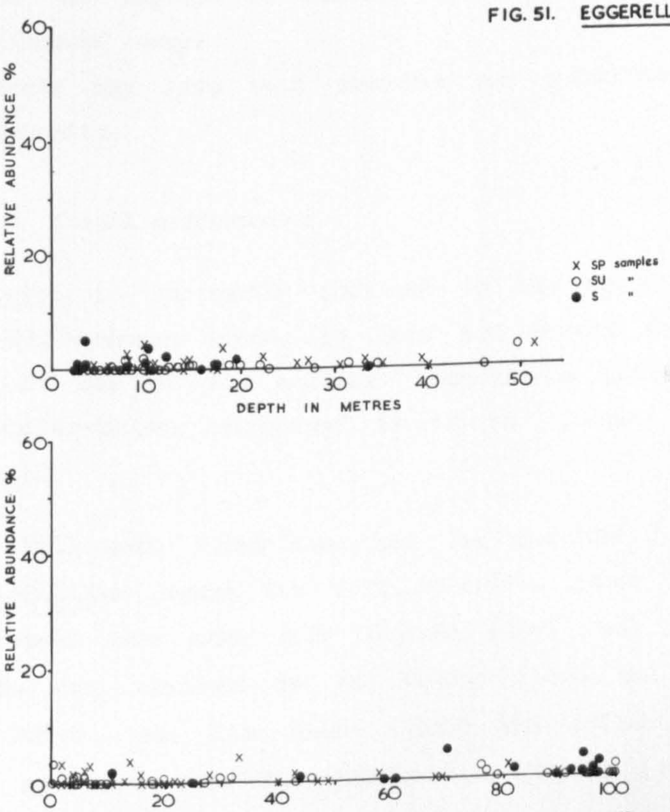


Fig. 50. Areal distribution of Eggerella scabra



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 51. **EGGERELLA SCABRA**



in the dead population are unknown but there are a number of possibilities:

1. The living population of E. scabra has recently decreased in relative abundance for some reason, possibly connected with an environmental change, and the dead population reflects this former abundance.
2. Post - mortem redistribution may have affected the distribution in any of the following ways:
    a) Tests may have been transported into the deltaic area from an area of high abundance elsewhere.
    b) Tests were observed in many of the dead populations to be large and it is possible that these are less easily redistributed by currents and build up in relative abundance at the expense of smaller species which are more readily winnowed away.
    c) Tests may have been reworked and concentrated from older deposits.

Recent and fossil occurrences:

E. scabra is apparently confined to the north European and western Mediterranean areas. It does not extend far back into the Tertiary and one of its earliest records is probably late Pleistocene; Fehling-Hansen recognized it in an 'Arctic' clay from near Oslo (1954).

When Williamson first described the species (1858) he mentioned several localites around the British Isles. Other records in the North European area come from Höglund (1947) who noted that dead tests were very abundant in the Gulmar Fjord and the Skagerak down to 205 m., and from Haake (1967) who collected both living and dead specimens from the Baltic Sea. Murray (1961) recorded it living in Christchurch Harbour and concluded that it is a marine steno - haline species probably occurring in greater abundance outside the harbour.

From the English Channel area it extends down the French coast to the coast of northern Spain. In the Mediterranean it appears to be confined chiefly to the northwestern part; the author has specimens from the Balearic Isles, the Rhône delta, Sicily, and from Rimini in the Adriatic. Montcharmont - Zei (1964) recorded it living in the Gulf of Naples and Blanc - Vernet (1963) noted that living specimens in the Gulf of Marseille have a sporadic distribution in both muddy and sandy sediments. Kruit (1955) observed that its distribution around the Rhône delta is marine in either muddy or sandy sediments irrespective of depth; he could find no optimum depth of occurrence.

It seems from the preceding records of the the species that E. scabra is largely a cool temperate species being most abundant in the cooler waters of the British Isles - North Sea area. Although it occurs commonly in the western Mediterranean it does not reach any great abundance and it is likely that the warmer Mediterranean waters are near to its upper temperature tolerance level. It is not found in samples from the North African coast or in the eastern Mediterranean and a summer temperature in excess of about 23° may be too high for the species to tolerate. The observations of Kruit, Murray and Blanc - Vernet confirm the conclusions drawn from the distribution of E. scabra around the Ebro delta that it is a species occuring in a wide depth range with no preference for a particular type of substrate.

Quinqueloculina schlumbergeri (Weisner)

In the spring highest relative abundance of Q. schlumbergeri is in the inshore assemblage off the southern spit. Percentages decrease appreciably with depth and only a few individuals are recorded in the offshore assemblage. In the southern lagoon percentages vary from 0 in the northeastern corner to 17 % near San Carlos harbour. The areal distribution map (figure 52) shows that there is a similar distribution pattern in the summer except that the area of highest relative abundance (> 20 %) on the southern delta flank extends farther north past the southern channel. Percentages are lower in the southern lagoon and the species is absent altogether from several stations there; the highest value of 10 % is recorded in the northeastern corner which is exactly the opposite of the spring trend. Few specimens are recorded in the northern lagoon but elsewhere on the northern side of the delta the pattern is much the same as on the southern side. Absolute abundances tend to higher than for the southern side (see figure 53).

Q. schlumbergeri has a depth range of < 3 - 50 m. but only flourishes in depths from 4 - 11 m. (figure 53). It has a preference for sandy substrates but many spring stations have high percentages in substrates of sand / mud mixtures. There does not, on the whole, seem to be a strong correlation of abundance and sediment type. In addition, despite the fact that the species only occurs abundantly within a relatively narrow depth range, there are many stations within this range where it is rare or non - existent. These are in the more sheltered situations such as the lagoon and transition areas. There is good correlation between high abundance and turbulence. Q. schlumbergeri appears to prefer the turbulent conditions that exist in the shallow water off the delta flanks over the delta front platform. There are few individuals recorded

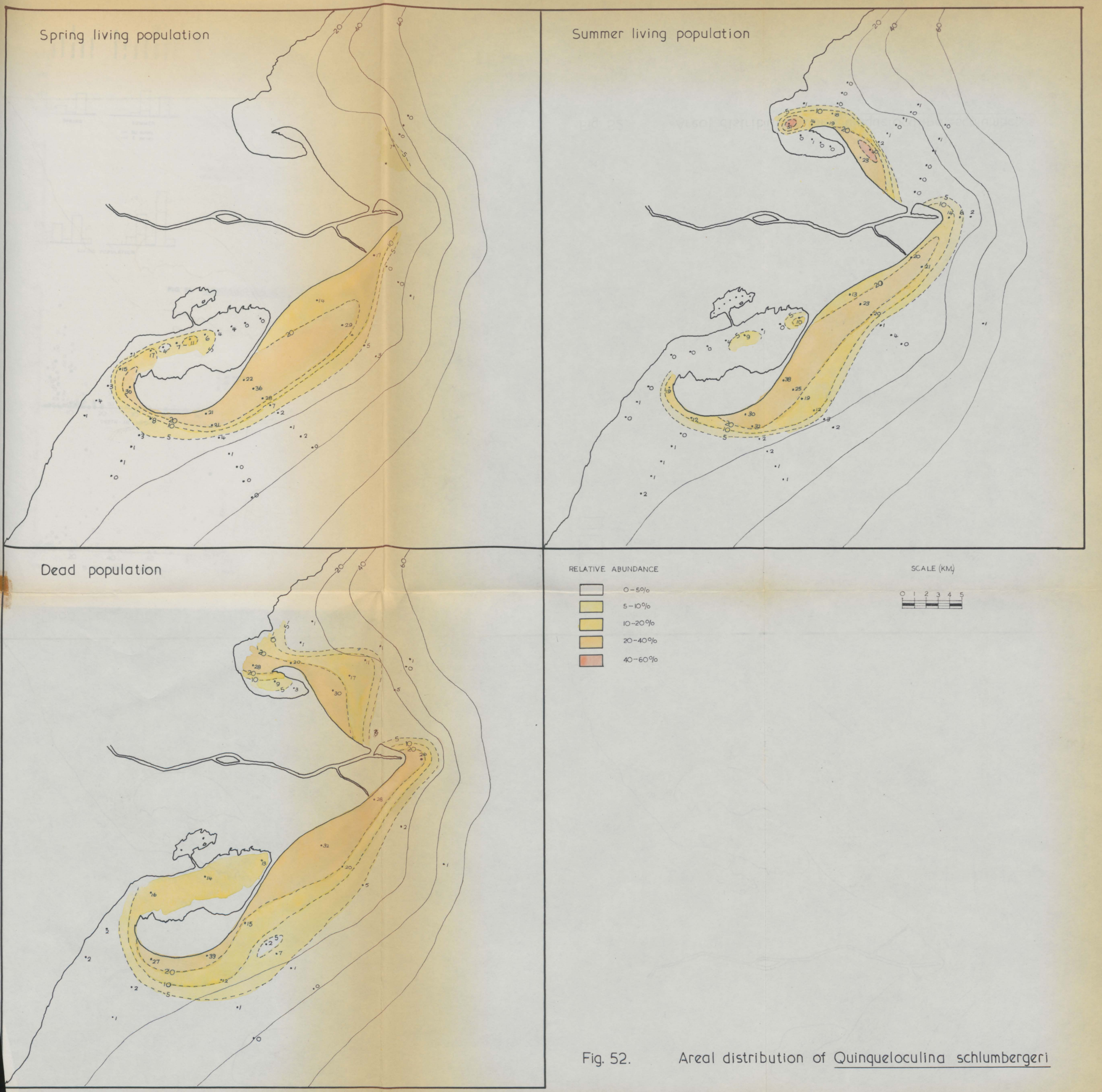
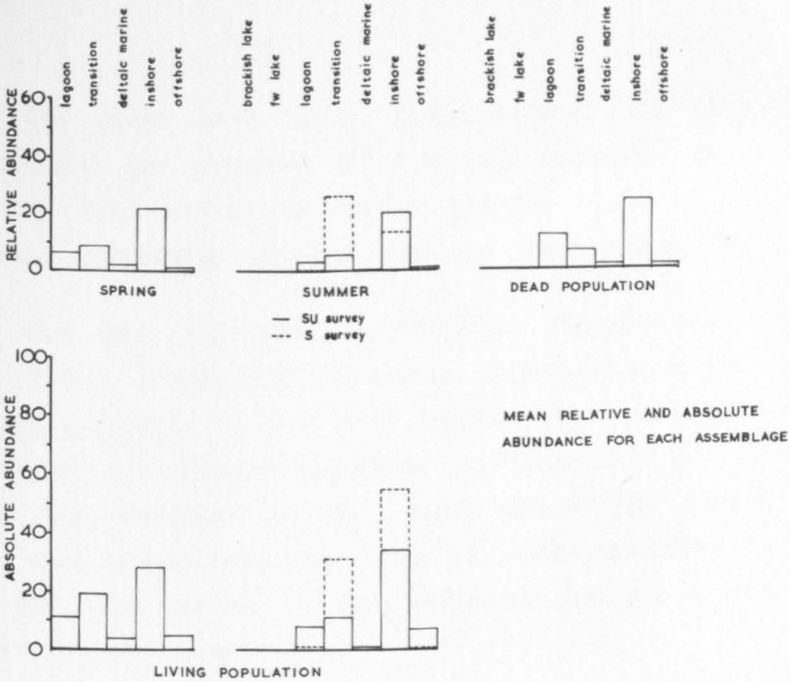
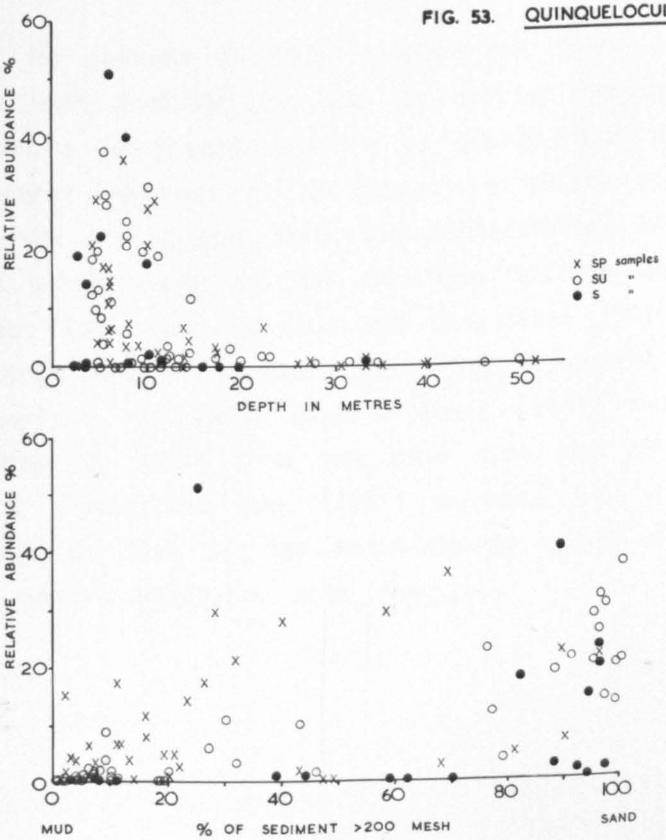


Fig. 52. Areal distribution of *Quinqueloculina schlumbergeri*



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 53. QUINQUELOCULINA SCHLUMBERGERI



off the river mouth which suggests that conditions of rapid sedimentation are adverse. Relative and absolute abundance do not vary greatly from spring to summer and it must be assumed that the species flourishes equally well in temperatures between 12 and 26°C.

The dead population distribution follows the same pattern as the living population indicating that post - mortem redistribution of Q. schlumbergeri is not very marked. Mean percentages for the different assemblages are close to those of the living population with the exception of the lagoon which has greater abundance in the dead population. The size of most specimens is close to that of the sand grains in the sediment; smaller specimens are probably winnowed away.

Fossil and recent occurrences:

No records of this species was found in any publication dealing with Tertiary deposits or in any Tertiary samples in the author's possession and it is likely that it is exclusively a 'recent' species. It is largely a Mediterranean species and it appears in samples from the Rhône delta, Sicily, Tripoli, Rimini and other areas in the Adriatic. Weisner collected the type specimens from the Adriatic and Sidebottom (1910) recorded it from Palermo harbour. Schlumberger (1893) observed it in the Gulf of Marseille and later Blanc - Vernet (1963) said that it is common living in sands from the same area and is very abundant in the dead population. Kurc (1961) recorded the species living in the Etang de Thau on the Mediterranean coast of France, particularly on sandy substrates with Zostera.

Triloculina sp.

In the spring Trilòculina sp. is widely distributed through all assemblages except in the deepest water, but it is generally only in low frequencies. (figure 54). The station with highest relative abundance, SP/41, is located close to the end of the southern spit in the transition area.

In the summer abundance is increased in all assemblages except the transition assemblage (figure 55). There is a marked area of high abundance in relatively shallow water off the southern spit with reasonably high abundance extending all along the southern delta flank and around the spit into the southern transition area. There is a similar area of high relative abundance off the northern side of the delta but abundance is low in both lagoons.

The abundance / depth plot in figure 55 shows that Triloculina sp. is found within a depth range of 2½ - 34 m. but it is only abundant within a narrow part of this range, generally less than 14 m. The sediment / abundance plot illustrates a distinct preference for sandy sediments although it does live in muddy sediments in low frequencies. The higher abundance in summer suggests a preference for warmer temperatures.

The dead population has very low relative abundance with no station exceeding 4 %. There must be considerable current redistribution of tests when living individuals die; the small size of the species means that it is easily transported by currents.

This species was not specifically identified and so it is impossible to define its modern and fossil distribution from the literature. However, it is present in samples from the English Channel area, northern Spain, Rhône delta, Sicily, Hammumet (Tunisia), and Rimini and so it appears that its modern distribution includes

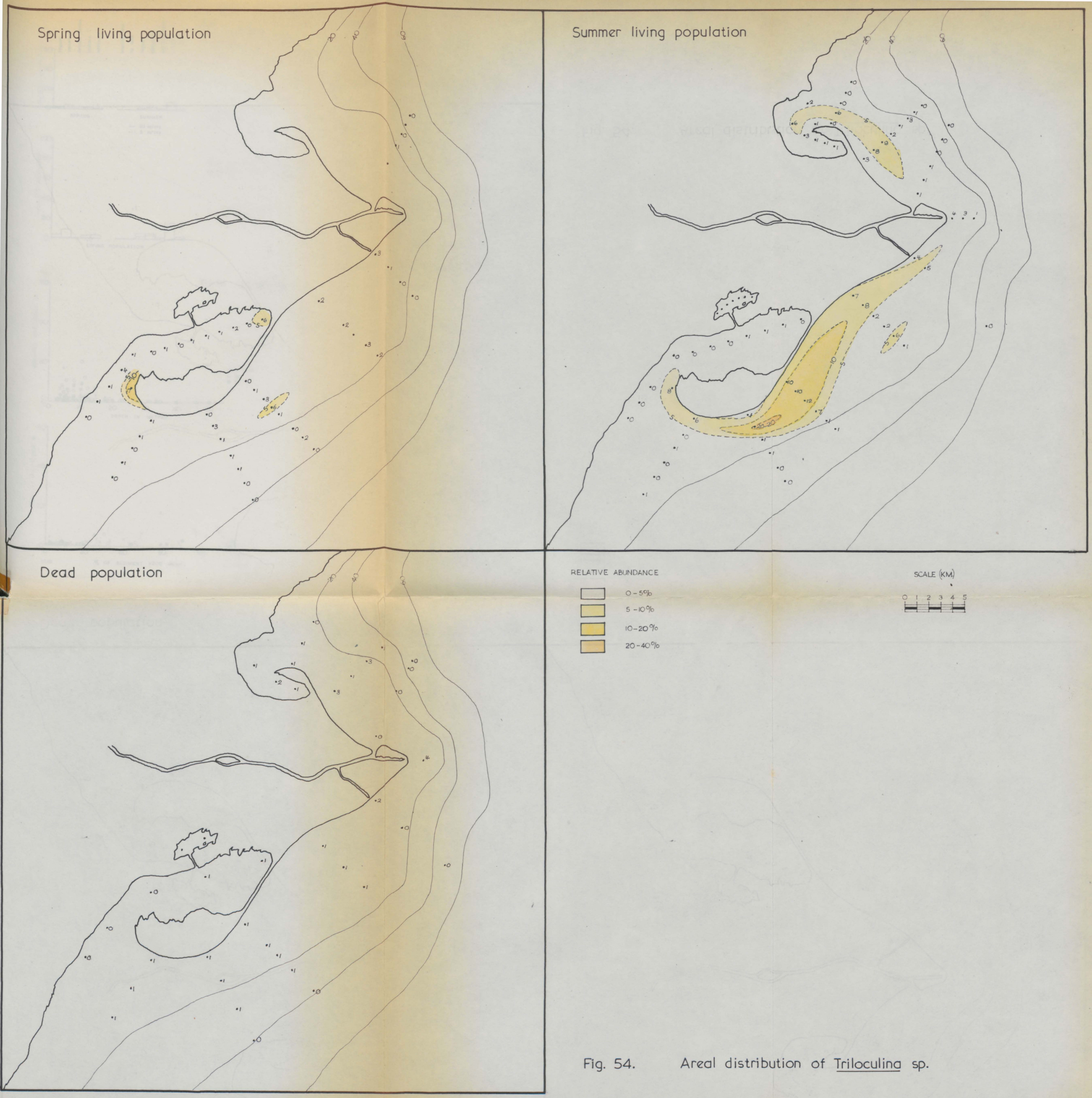
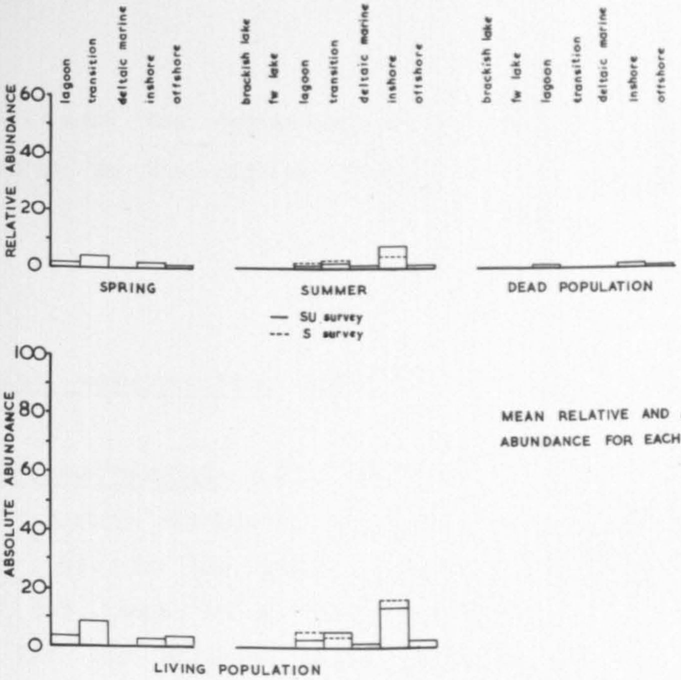
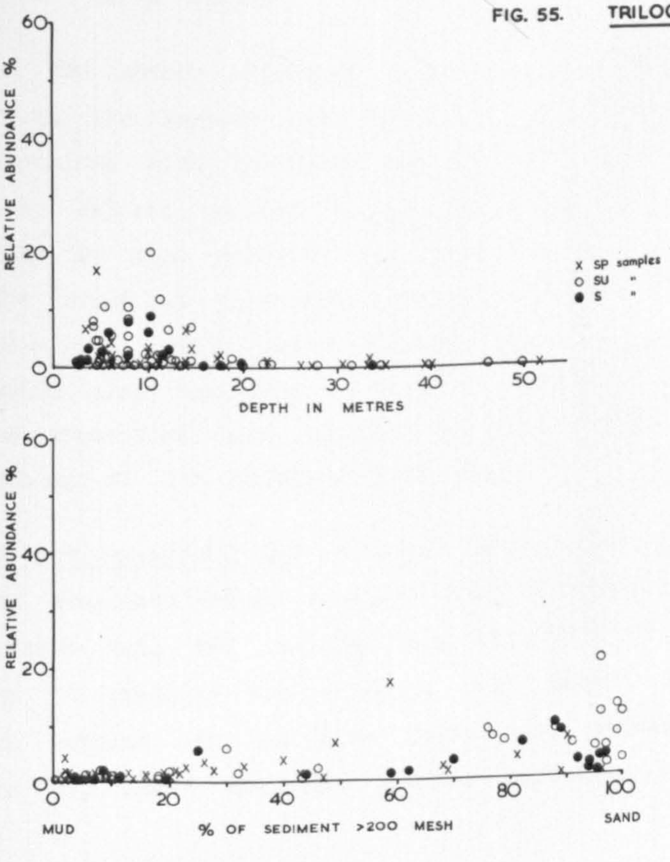


Fig. 54. Areal distribution of Triloculina sp.



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 55. **TRILOCULINA** SP.



at the least the Mediterranean and Atlantic coasts of Europe as far north as the English Channel.

Brizalina pseudopunctata (Höglund)

B. pseudopunctata is a very common species around the Ebro delta occurring abundantly at most stations with normal salinity (figure 56). In the spring percentages are low in the southern lagoon but there is a distinct 'high' in the adjacent transition area. Off the southern delta flank relative abundance is low close to the shore but increases with depth to a maximum in the 18 - 25 m. depth range.

In the summer abundance increases considerably. Percentages are higher in the lagoons and the high in the southern transition area is maintained with increased relative and absolute abundance. In addition, deltaic marine, inshore and offshore assemblages show increases in mean relative and absolute abundance values (figure 57), but the trend of increasing abundance with depth to a maximum in the 18 - 25 m. depth range remains the same. The northern side of the delta also has this pattern of distribution but the 'high' in the transition area appears to be continous with the higher percentages of the offshore assemblage.

B. pseudopunctata has a depth range from $2\frac{1}{2} \rightarrow 53$ m. with maximum abundance within a range from 5 - 33 m. Following this percentages tail off and the deepest limit of occurrence of the species is probably not a great deal deeper than the deepest station sampled off the Ebro delta. The sediment / abundance plot (figure 57) shows that the species can live in all grades of

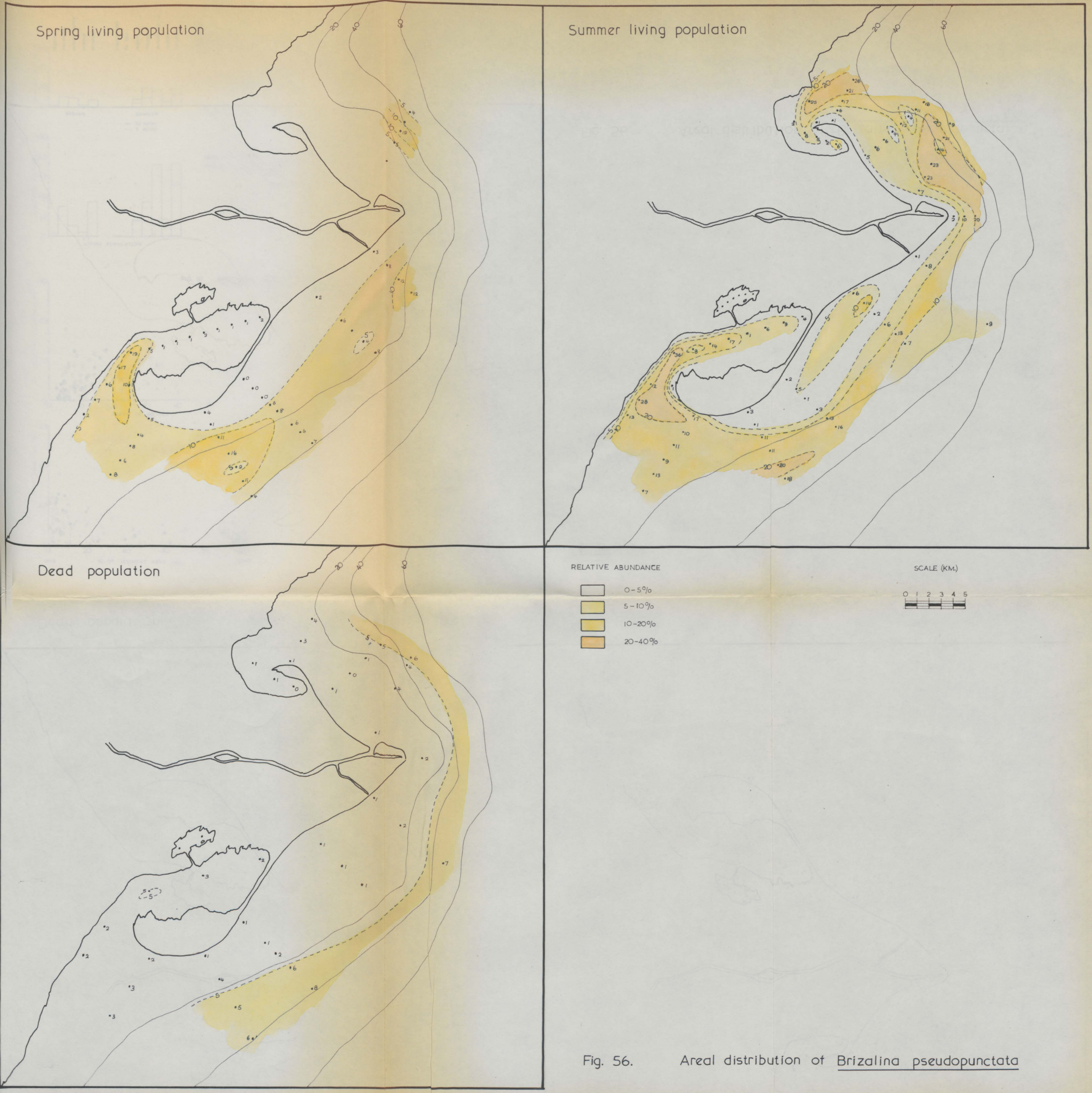
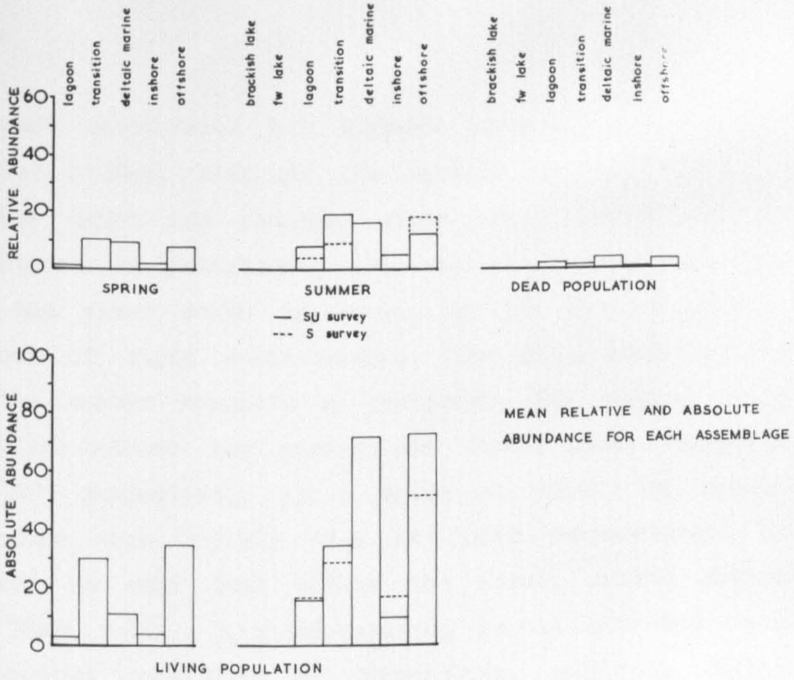
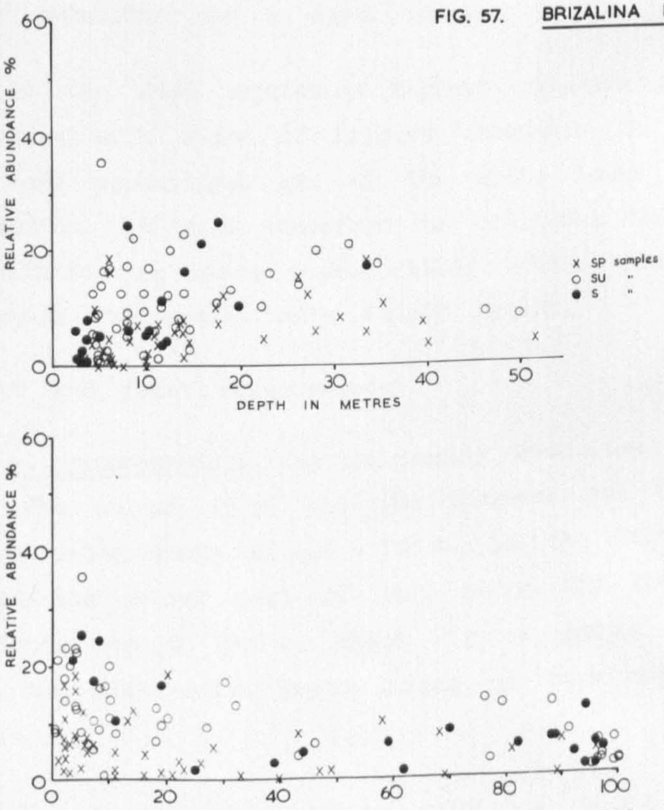


Fig. 56. Areal distribution of Brizalina pseudopunctata



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 57. **BRIZALINA PSEUDOPUNCTATA**



sediment encountered but highest percentages tend to be in the muddier grades. Although the species has an optimum depth range, neither depth nor sediment alone seems to be of over - riding importance in determining its abundance. High abundance is recorded off the river mouth in summer so it can obviously tolerate conditions of rapid sedimentation. The all - round increase in abundance in the summer suggests a preference for warmer temperatures and somewhere between the spring and summer mean temperatures of 15 and 25° respectively is a value at which the species begins to reproduce more rapidly than at lower temperatures. In conclusion it can be said that within the normal marine environments around the Ebro delta, B. pseudopunctata is an abundant species tolerant of various conditions of temperature, sediment, depth and turbulence, but it has an optimum response to temperatures around 25°, a muddy substrate and a depth between 5 and 33 m.

In the dead population highest relative abundance usually coincides with areas of highest abundance in the living population but mean percentages are on the whole lower than for the living population. It must therefore be concluded that post - mortem redistribution is quite considerable; bottom currents can probably transport the small tests fairly easily.

Recent and fossil occurrences:

B. pseudopunctata was originally described by Höglund (1947) from the Gulmar Fjord and the Skagerak and he noted that it has a depth range of 26 - 118 m. in the Gulmar Fjord but preferred the deeper part of this range. In the Skagerak it occurred in depths up to 500 m. These figures cannot be compared directly with the Ebro delta depth ranges as they refer only to dead specimens.

The species seems to be solely a recent one; no record could be found in the Upper Tertiary unless it has been wrongly identified as B. punctata (d'Orbigny). There are records of the species living in the English Channel area; Murray (1965a) reports it off Plymouth and in Christchurch Harbour while the author has specimens from the French side of the Channel and from Brittany. In the Mediterranean it occurs commonly in the northwestern area and in the northern part of the Adriatic. Blanc - Vernet (1963) observed that the species lives abundantly in muddy sediments in the Gulf of Marseille but is less abundant in sands.

Bulimina aculeata d'Orbigny

The areal distribution of B. aculeata is illustrated in figure 58. In the spring it only occasionally attains more than 10 % relative abundance. There is a small area of high abundance in the southern transition area but there are very few occurrences in the southern lagoon. There appears to be no connection between the former high and the high percentages in deep water southeast of the southern spit. B. aculeata is generally rare on the delta front platform but abundance increases with depth and the offshore assemblage has the highest mean number of individuals per sample (figure 59). The deltaic marine assemblage has highest mean relative abundance.

In the summer there is a general increase in abundance. Although there are a few more individuals in the southern lagoon, the high in the transition area has disappeared. Off the delta flanks there is an increase in percentages and the 5 % contour (figure 58) consequently runs closer to the shoreline. The high southeast of the southern spit in water deeper than 20 m. is

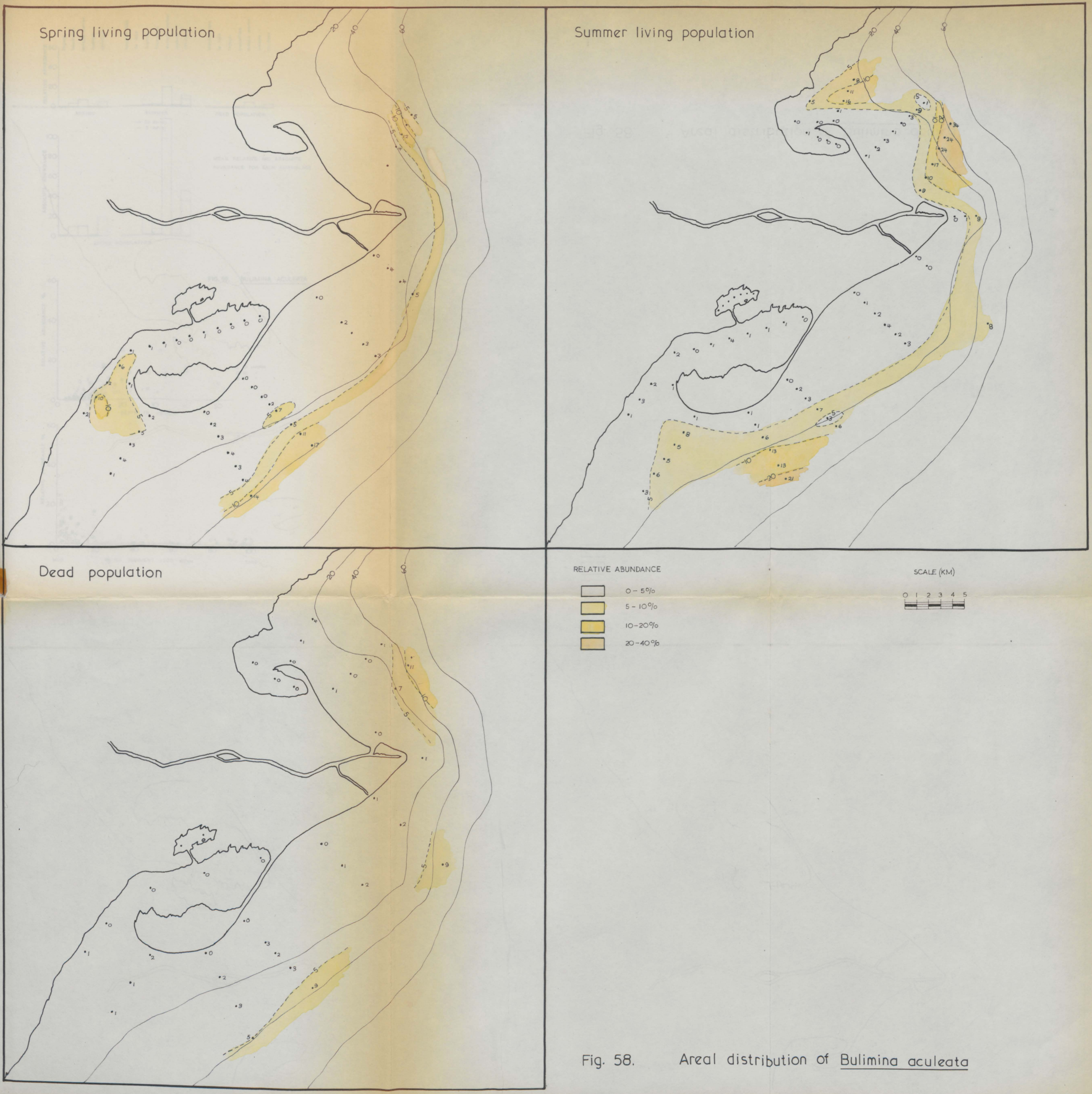


Fig. 58. Areal distribution of Bulimina aculeata

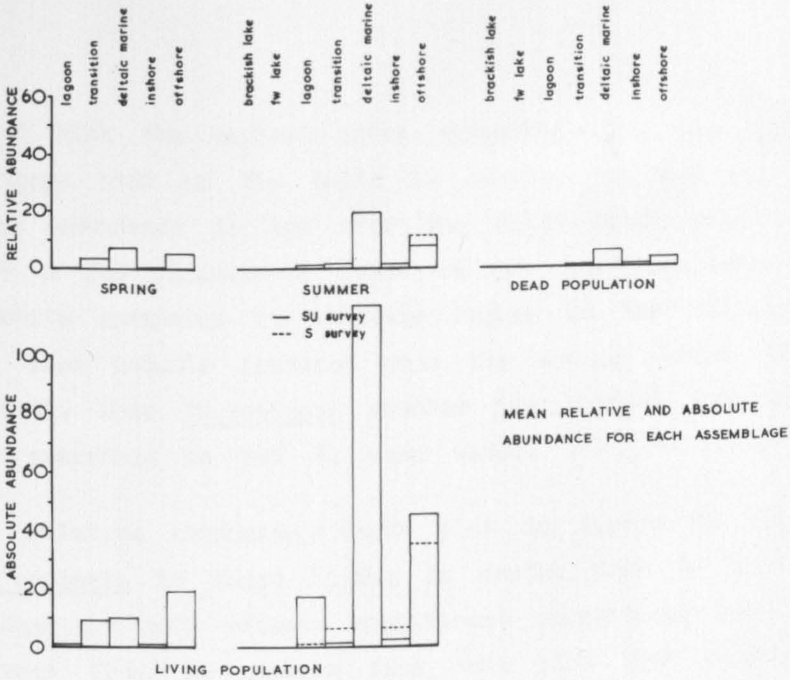
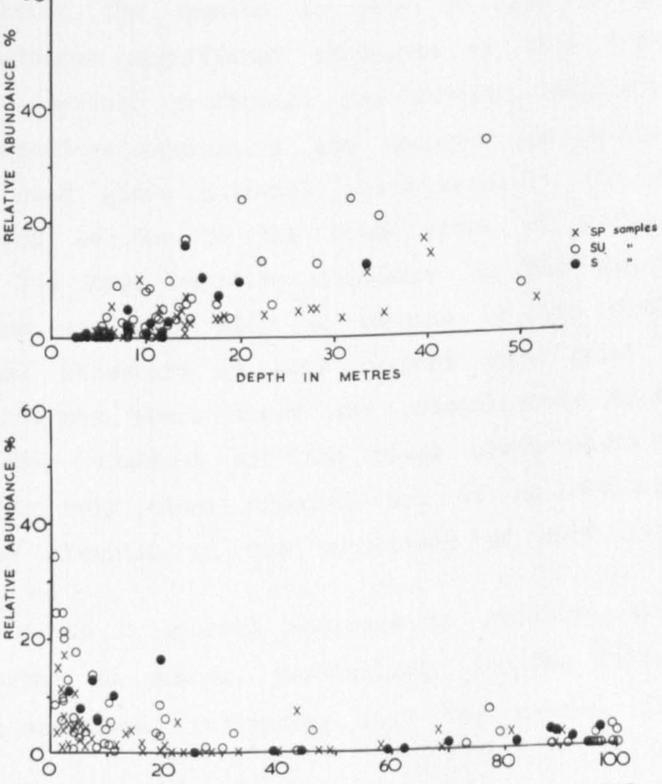


FIG. 59. **BULIMINA ACULEATA**



maintained with the highest value exceeding 20%. The pattern on the northern side of the delta is similar to that on the southern side; abundance is low over the delta front platform and there are only a few individuals found in the northern lagoon. Relative and absolute abundance is slightly higher in the offshore assemblage but the most notable increase over the spring survey is off the river mouth. Here B. aculeata reaches its highest abundance, rising from 9% nearshore to 34% in deep water.

The relative abundance / depth plot in figure 59 illustrates that B. aculeata is found living in depths from 4 to at least 53 m. although it only attains significant percentages (more than 20%) deeper than 19 m. It appears from this plot that relative abundance may increase even more with further depth.

Although the species is able to live in sandy substrates it rarely attains significant abundance on this type of substrate. It shows a distinct preference for muddier sediments; practically all high percentage occurrences are recorded in sediments with less than 10% of sand grade material. Occurrences in the southern lagoon in summer may be due to the finer grade of sediment compared to the spring. Its high relative abundance in the shallow water of the transition area may also be because of its preference for muddy sediments. Elsewhere it only reaches this order of abundance at greater depths where there are predominantly muddy sediments. It is particularly abundant off the river mouth where sediments are favourable from very close inshore, and it is obviously able to tolerate and even flourish in the conditions of very rapid sedimentation.

There is a general increase in relative and absolute abundance from spring to summer, particularly in the deltaic marine and offshore assemblages, indicating that the species flourishes better in warmer temperatures. Many juvenile individuals were observed in the summer counts so the species had recently undergone, or was in the middle of, a phase of relatively rapid reproduction.

The dead population is distributed on the same lines as the living population. The greatest concentration of empty tests is off the river mouth and elsewhere there is a general increase in relative abundance with depth. However, mean relative abundance values for the various assemblages are considerably lower than for the corresponding values for the living population and it must be concluded that post - mortem redistribution of tests of B. aculeata is quite considerable.

Fossil and Recent occurrences:

The type specimen of B. aculeata was collected from beach sand at Rimini on the Italian Adriatic coast, but it also recorded commonly from the Upper Tertiary. Cushman (1946) noted that it has been recorded from the Miocene of Kattowitz, Germany, Dax in France and Buff Bay, Jamaica. In the Eurpopean Pliocene and Pleistocene it is common at a number of locations; for example, the East Anglian crags (Plioc/Pleist) and the Calabrian of Italy.

There are a great number of records of the species from modern sediments all over the world. It is very common in the Mediterranean; it has been recorded living in the Bay of Naples (Montcharmont - Zei, 1964), in deep water off Capri (Botteron, 1958) and Blanc - Vernet (1963) noted that it is abundant in muds in the Gulf of Marseille. This last record is interesting because it bears out the ecological conclusions drawn from the distribution off the Ebro delta. Blanc - Vernet also noted that B. aculeata is rarer in sandy sediments; all his sampling stations were in slightly deeper water than the Ebro stations (50 - 80 m.) but again substrate seems more important than depth in influencing the distribution of the species.

It is also recorded living in the English Channel area but Cushman (1946) noted that it is generally rare around the coasts of Great Britain and Belgium. Other records come from the Pacific, Australian, Japanese and Antarctic regions so it appears that the spcies is very widespread.

B. aculeata has for a long time been recognized as a relatively deep water species. For example, Bandy and Chierici (1966) said that the upper depth limit in the Mediterranean, Gulf of Mexico and Antarctic was between 250 and 300 m. They did not, however, use staining methods for distinguishing living specimens and it appears from the distribution of B. aculeata around the Ebro delta that it can live in much shallower water than has often been thought.

Hopkinsina pacifica var. atlantica Cushman

This species has a very restricted distribution. In the spring the highest percentages are found in the southern lagoon with two stations exceeding 10%. The species extends in smaller numbers through the transition area but in open marine areas occurrences are rare. (Figure 60).

In the summer survey there is a similar distribution pattern with highest relative abundance in the western part of the southern lagoon and irregularly along the Las Casas traverse. The species is absent from most stations on the northern side of the delta and there is no high abundance in the lagoon and transition

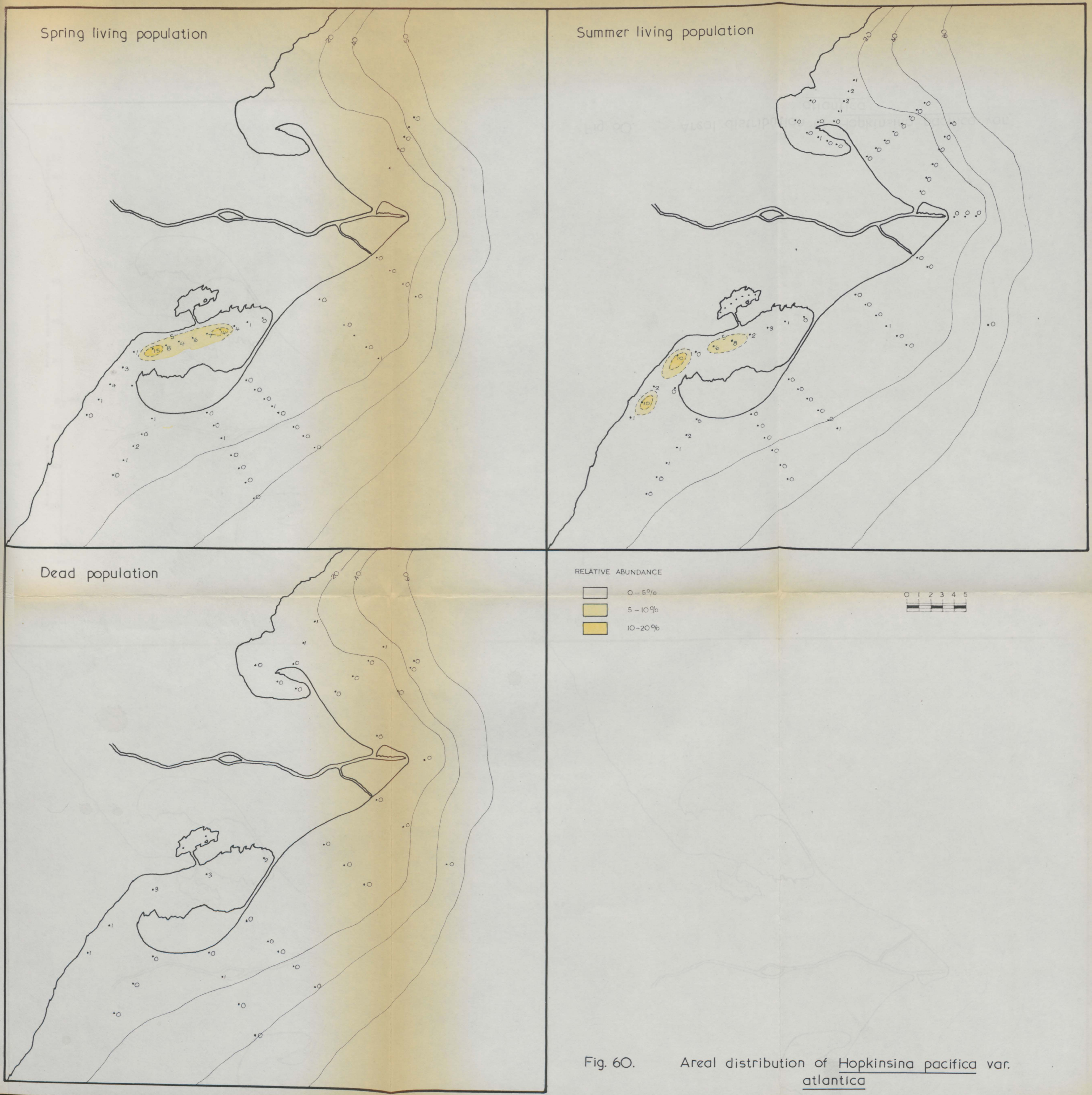
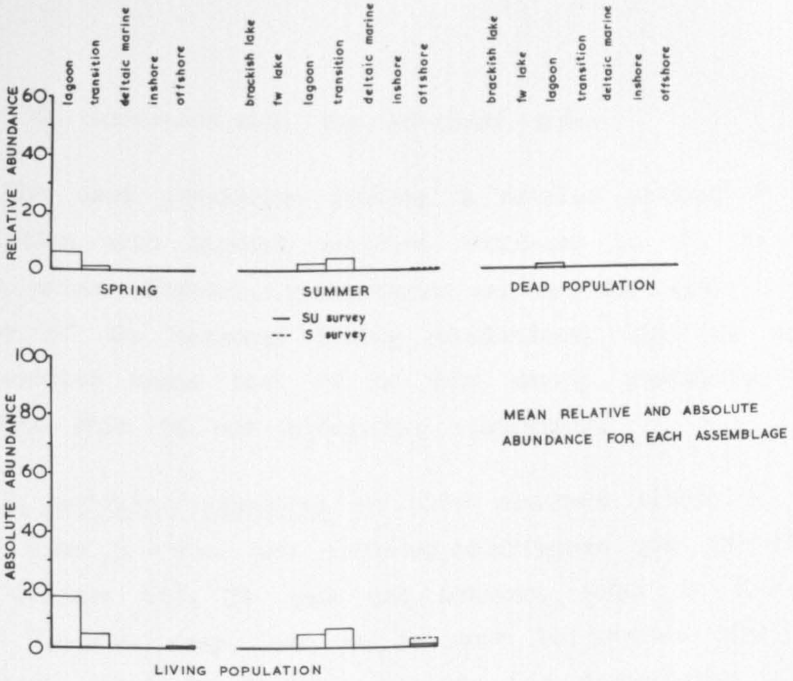
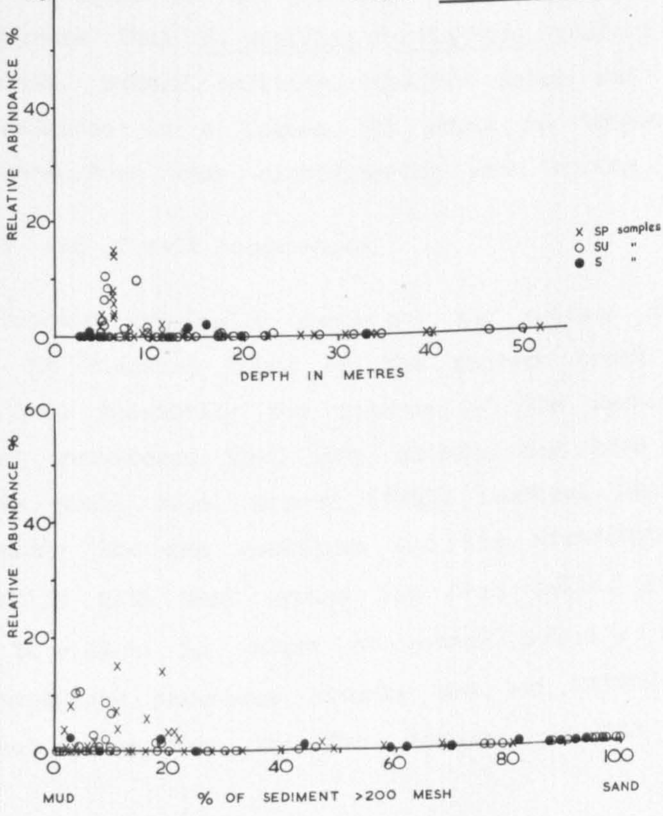


Fig. 60. Areal distribution of *Hopkinsina pacifica* var. *atlantica*



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 61. HOPKINSINA PACIFICA VAR. ATLANTICA



area to correspond with the southern side.

The dead population follows a similar pattern to the living population with highest relative abundance in the lagoon and transition areas. However, percentages are on the whole lower than for either of the seasonal living populations, but the small size of the species means that it is very easily redistributed by currents so that this is not altogether surprising.

H. pacifica / atlantica is only abundant within a narrow depth range from 5 - 9 m. but isolated occurrences are recorded down to 46 m. (figure 61). It does not, however, occur in all areas with water 5 - 9 m. deep, and so it must be assumed that depth is not the most important factor governing its distribution. The relative abundance / sediment plot in figure 61 shows that practically all the occurrences of the species are in muddy sediments. In summary, it appears that H. pacifica / atlantica prefers conditions of muddy sediments, normal salinity, shallow water and a situation around the entrance to a lagoon. It shows no temperature preference since abundance does vary significantly from spring to summer.

Recent and fossil occurrences:

Cushman originally described the species from a station of 11 m. depth in Vineyard Sound on the eastern coast of the U.S.A. There have been relatively few records of the species since then but Cushman considered that many authors may have overlooked it because of its small size. Murray (1968) recorded the species from Buzzard's Bay along the same coastline and its distribution there shows some similarity with that around the Ebro delta. It is found in depths from 12 - 24 m. in waters of normal salinity and Murray noted that the abundance increases towards the bay entrance. Temperatures are somewhat lower than the Ebro lagoons, ranging from 1 - 22°, and it occurs in both muddy and sandy sediments.

H. pacifica / atlantica was not found in any other Mediterranean samples and so its distribution can only be fixed to date as being the eastern seaboard of the U.S.A. and around the Ebro delta.

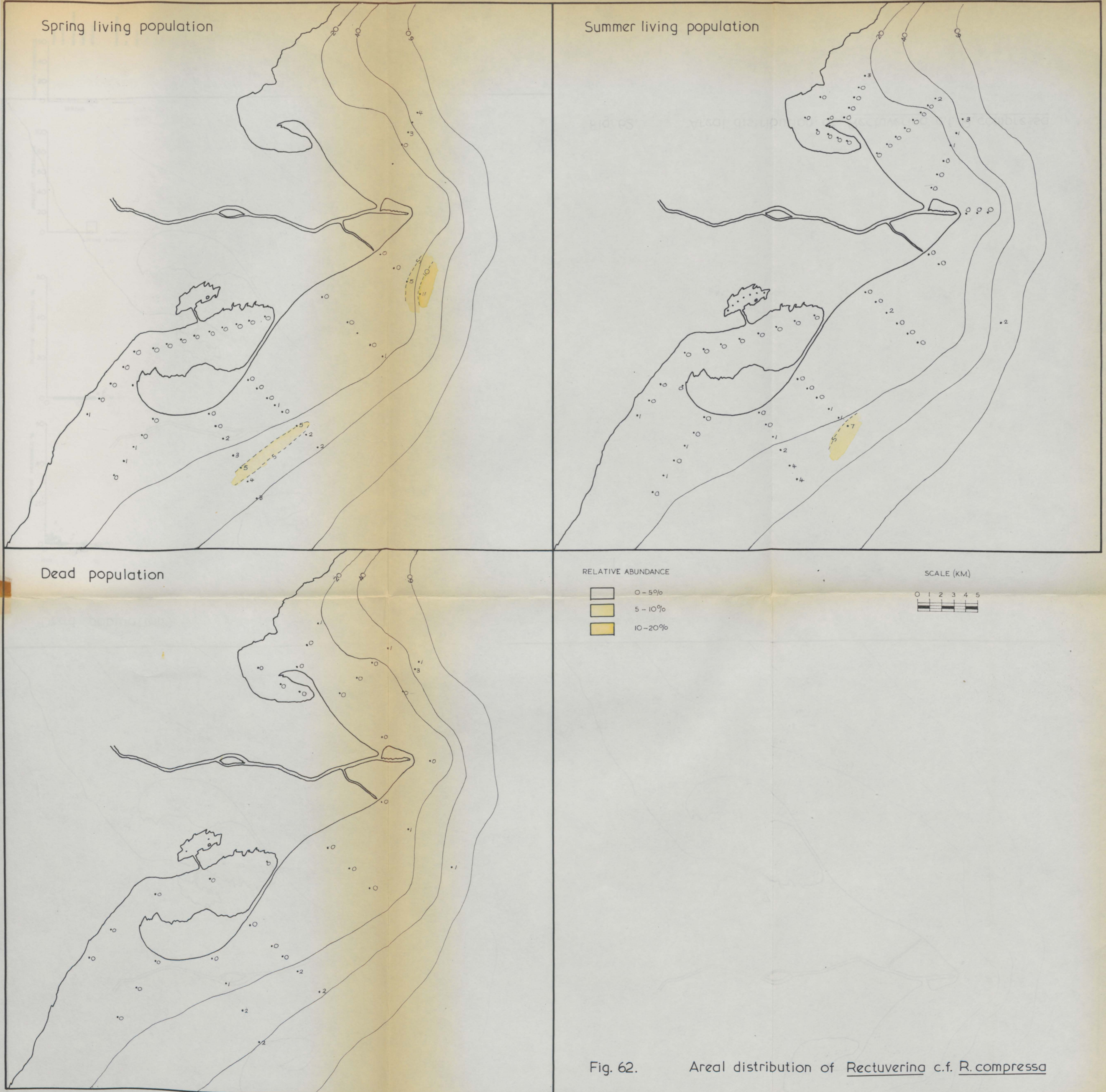
Rectuvigerina c.f. R. compressa (Cushman)

R. c.f. compressa is usually common in low frequencies in deeper water stations; in the spring it is most abundant in deeper water on the southern channel traverse. It is absent from the lagoon and inshore assemblages but has a wide distribution through the deltaic marine and offshore assemblages (figure 62).

In the summer a similar pattern of distribution is apparent. Samples were not taken in the deeper water of the southern channel traverse so it is not known whether the spring high persists. On the northern side of the delta there are also only records from deeper water. Mean relative abundance values are slightly lower than in spring although absolute abundance is slightly higher. (figure 63).

R. c.f. compressa was found living in depths from 11 - more than 53 m. and there is an apparent peak of abundance at about 27 m. From this peak percentages fall off but the species probably extends for some depth beyond 53 m. at fairly low frequencies. The abundance / sediment plot (figure 63) demonstrates a preference for muddy sediments and it appears that R. c.f. R. compressa favours an environment of relatively deep water of normal salinity away from the nearshore turbulent zone and a muddy substrate. There is no significant change in abundance from spring to summer and so no temperature preference can be inferred.

The dead population follows the distribution pattern of the

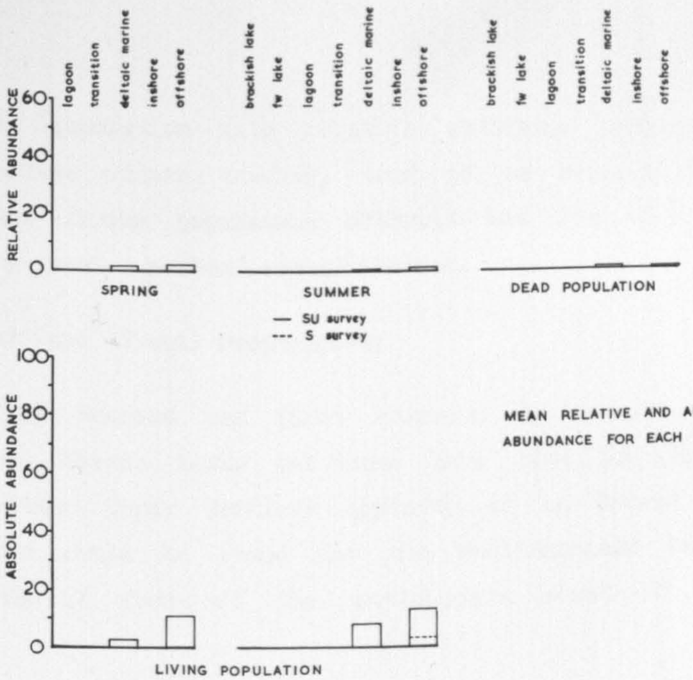


Spring living population

Summer living population

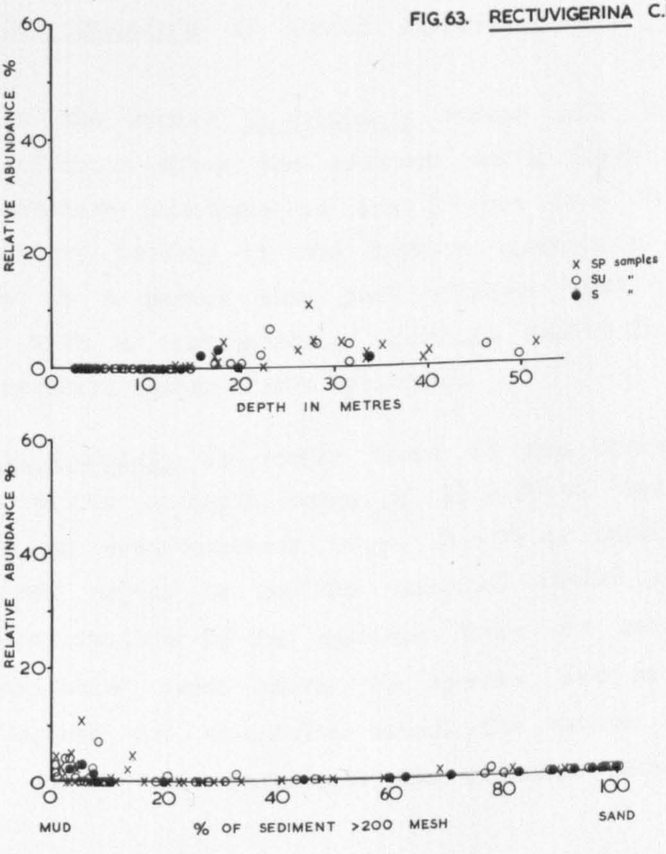
Dead population

Fig. 62. Areal distribution of Rectuverina c.f. R. compressa



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 63. RECTUVIGERINA C.F. R. COMPRESSA



living population with relative abundance increasing with depth. Percentage values, however, tend to be slightly lower than those of the living population although not low enough to suggest any strong post - mortem redistribution.

Recent and fossil occurrences:

The species was first recorded by Cushman from the Miocene of the Vienna Basin but there have been few records of the species in either Upper Tertiary deposits or in Recent sediments. No other records could be found for the Mediterranean but Colom (1952) records it from off the northwestern coast of Spain.

Eponides granulata di Napoli Alliata

In the spring _E. granulata_ occurs only in a restricted area just offshore along the southern delta flank and both relative and absolute abundance is low (figure 64). In the summer abundance is higher, notably in the inshore assemblage. Highest abundance occurs in a narrow zone just offshore from the southern delta flank with a corresponding, although relatively wider, zone over the northern delta front platform.

E. granulata is rarely found in the offshore assemblage; it lives within a depth range of $2\frac{1}{2} - 17\frac{1}{2}$ m. and is only abundant within an even narrower range, 8 - 15 m. Depth itself, however, does not appear to be the principal factor governing the occurrence and distribution of the species; there are several areas of water of 'suitable' depth where the species does not occur, such as in the lagoons and transition areas. The nature of the substrate seems to be more important. The relative abundance / sediment plot

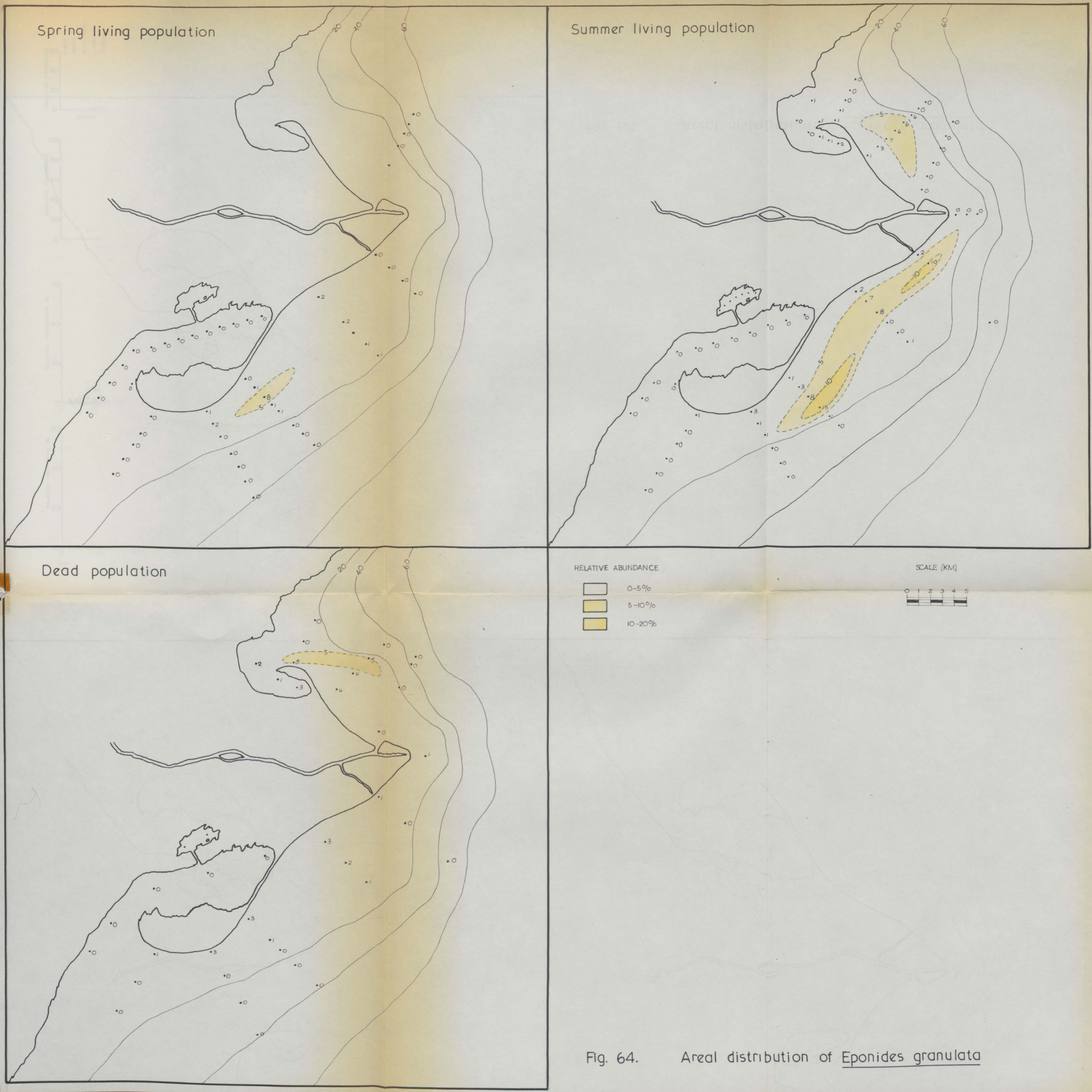
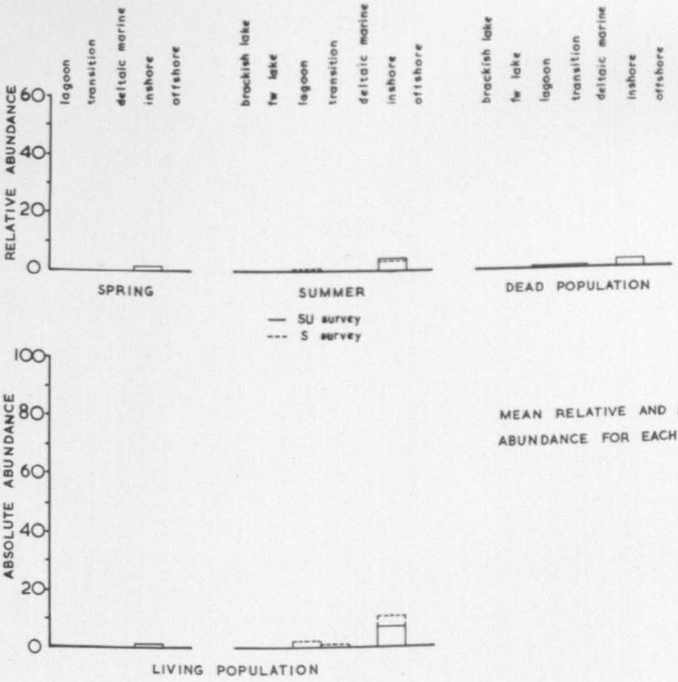
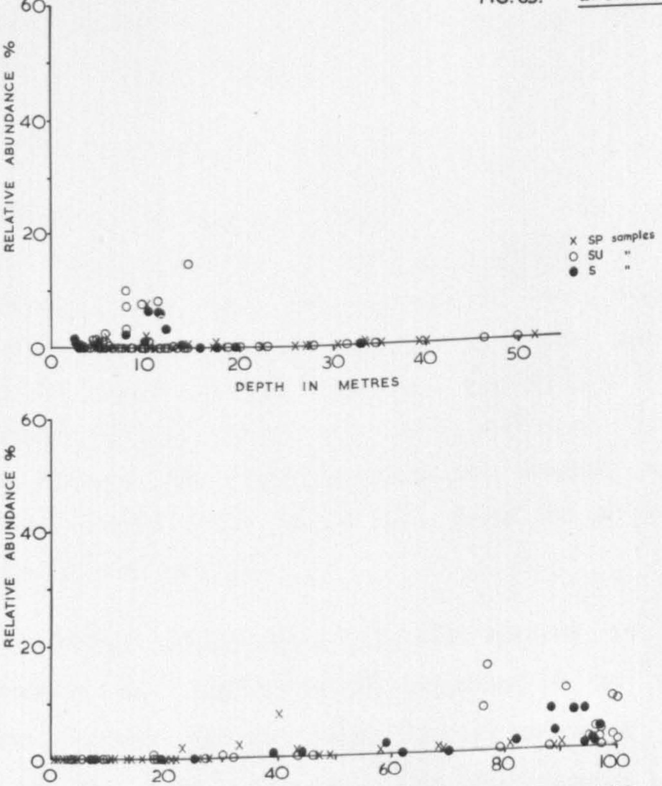


Fig. 64. Areal distribution of Eponides granulata



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 65. EPONIDES GRANULATA



(figure 65) illustrates that E. granulata occurs only in sandy sediments. It apparently cannot tolerate muddy sediments whereas sandy sediments, and the turbulent conditions associated with them, provide a much more favourable environment. The higher abundance in summer suggests a preference for warmer temperatures and a summer period of reproduction. Optimum conditions for E. granulata as observed around the Ebro delta can be summarized as a sandy substrate, a depth of 8 - 15 m., normal salinity and temperatures around 25°C.

The dead population has a distribution similar to the pattern shown by the living population. Mean relative abundance values for the different assemblages are slightly higher than for the spring but slightly lower than for the summer living population values. Abundance is low over the southern delta front platform in relation to living population figures and this may well reflect the strong currents in operation here.

Fossil and Recent occurrences:

Unless occurrences in other parts of the world have been recorded under different names, E. granulata is restricted to the Mediterranean area. The type specimens were collected from the Upper Pliocene of Castell Arquato in Italy and there are also records in Italy as far back as the Middle Pliocene. The species may extend further still into the Tertiary; the author has several Miocene samples from the Mediterranean region in which a very similar form occurs. The oldest of these is a Lower Miocene sample from the Rhône Valley.

The modern distribution of the species is chiefly the western Mediterranean but Parker (1958) recorded it in sediment samples from the eastern Mediterranean. Montcharmont-Zei (1964) recorded it living in the Gulf of Naples and the author has specimens from

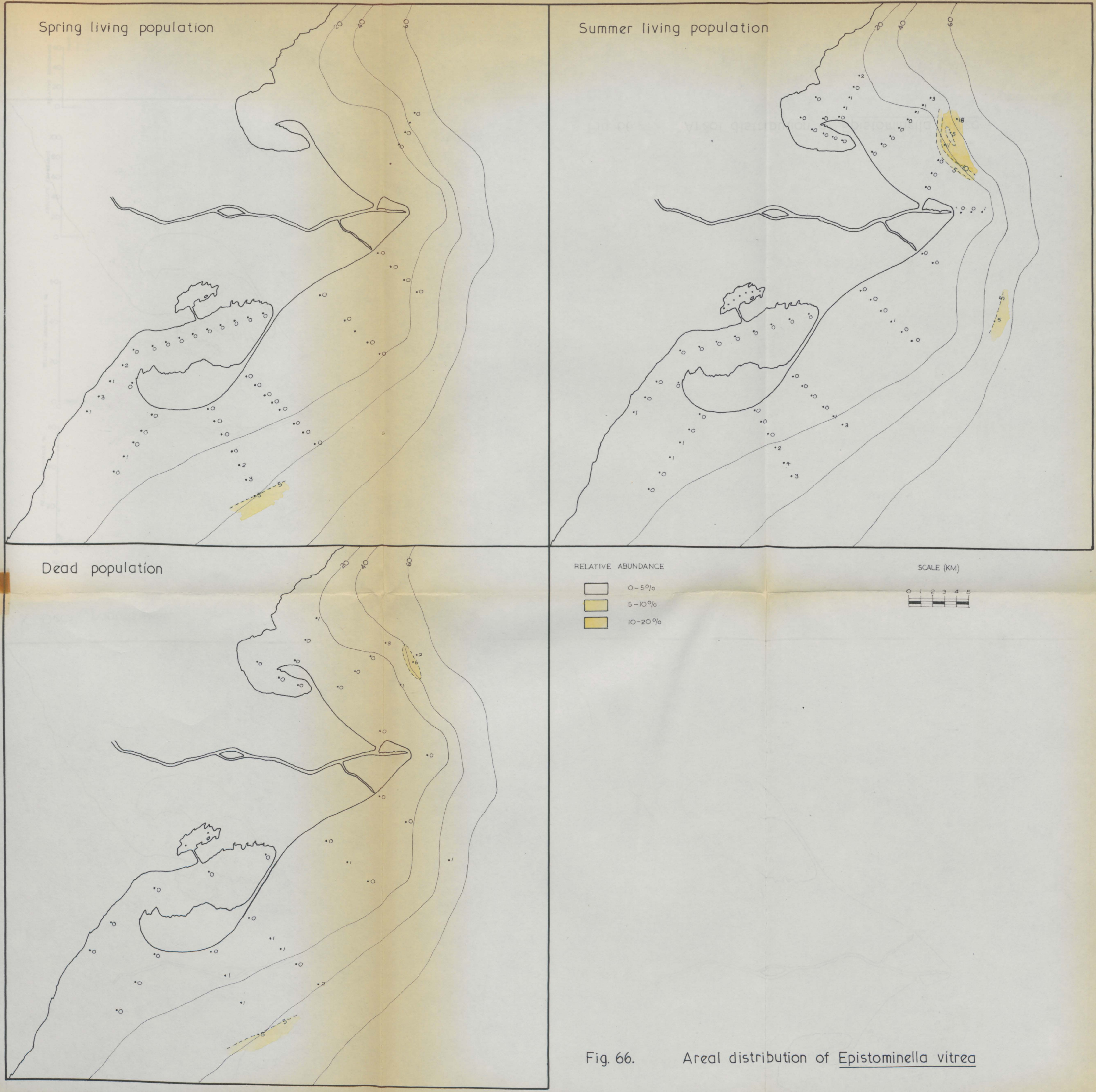
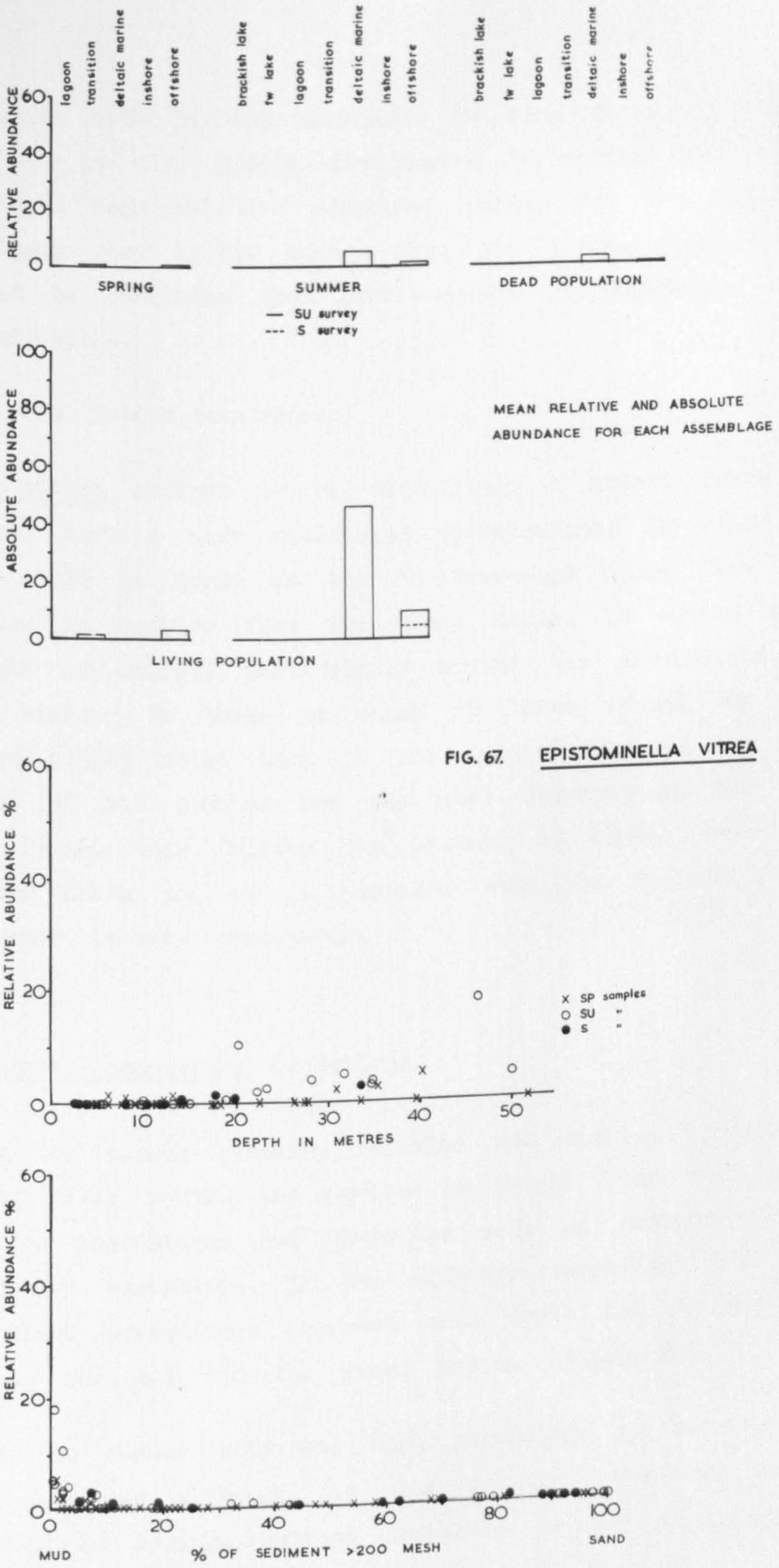


Fig. 66. Areal distribution of Epistominella vitrea



population with highest abundance in deep water off the river mouth. It is also widely distributed throughout the offshore assemblage. Mean relative abundance values for the different assemblages show little change from the living population and so it must be concluded that post - mortem redistribution of E. vitrea is negiligible.

Fossil and Recent occurrences:

E. vitrea appears to be exclusively a modern species but it does not have a very widespread distribution. No other records of it could be found in the Mediterranean apart from a few specimens in samples from the Rhône delta. It occurs commonly in the Gulf of Mexico, particularly around the Mississippi delta in depths similar to those in which it lives around the Ebro delta. Lankford (1959) noted that it was consistently in low frequencies in most of his samples but was most abundant in the deltaic marine fauna. This follows the pattern of highest abundance off the Ebro delta and it is possible that the species flourishes best under deltaic conditions.

Valvulineria complanata (d'Orbigny)

In the spring greatest relative and absolute abundance occurs off the river mouth. The species is absent from the lagoon and transition assemblages and there is only an isolated occurrence in the inshore assemblage. In the offshore assemblage off the southern delta flank percentages incresse with depth but do not reach the abundance recorded off the river mouth. (Figure 68).

In the summer only one high percentage is recorded off the river mouth and although the mean relative abundance is considerably less than in spring, absolute abundance is not significantly less.

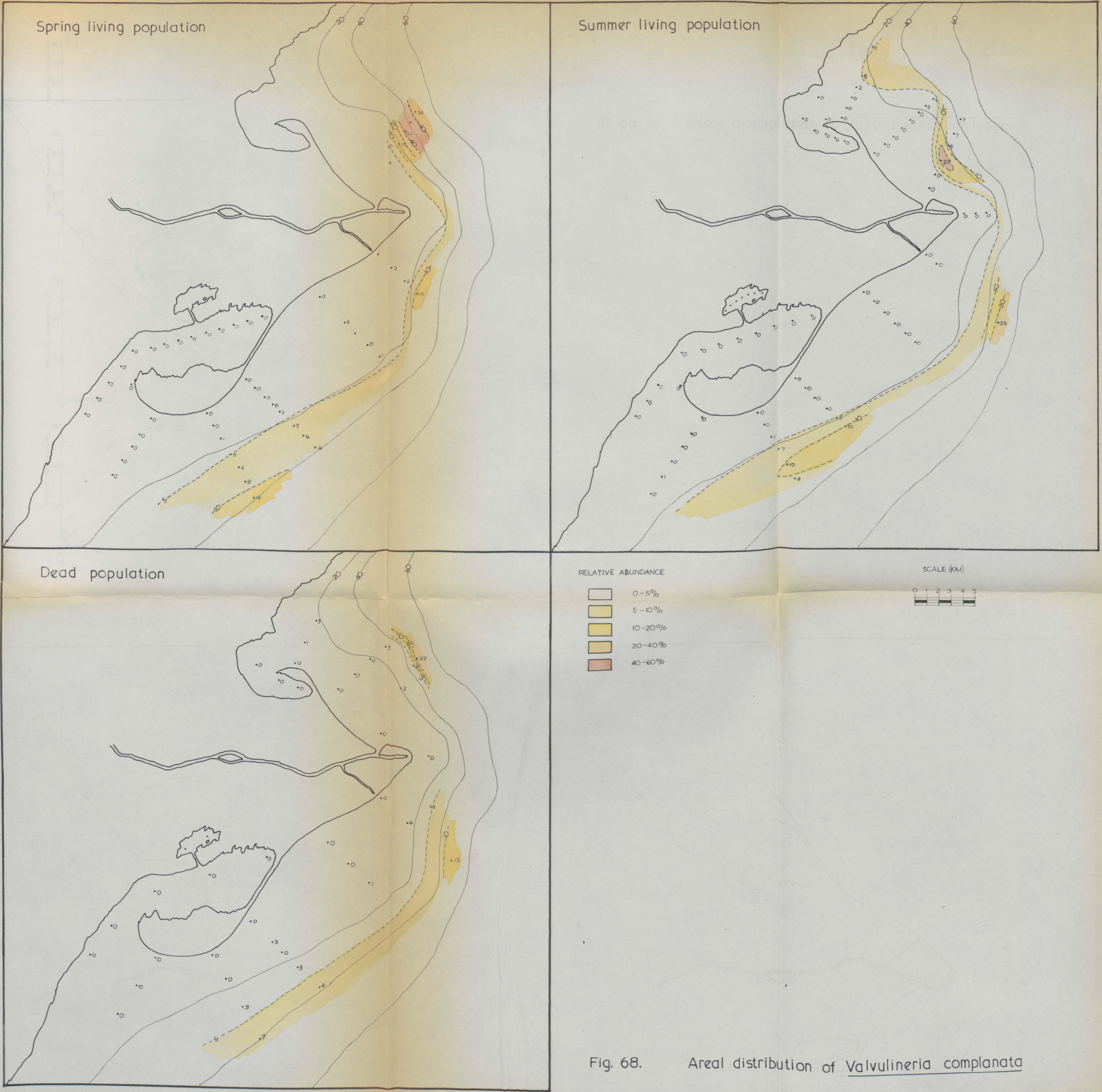


Fig. 68. Areal distribution of Valvulineria complanata

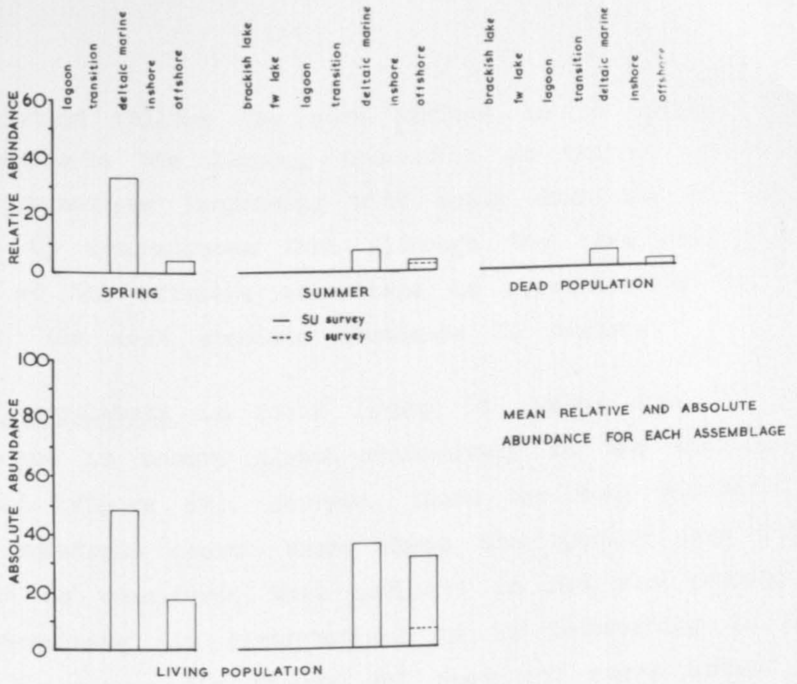
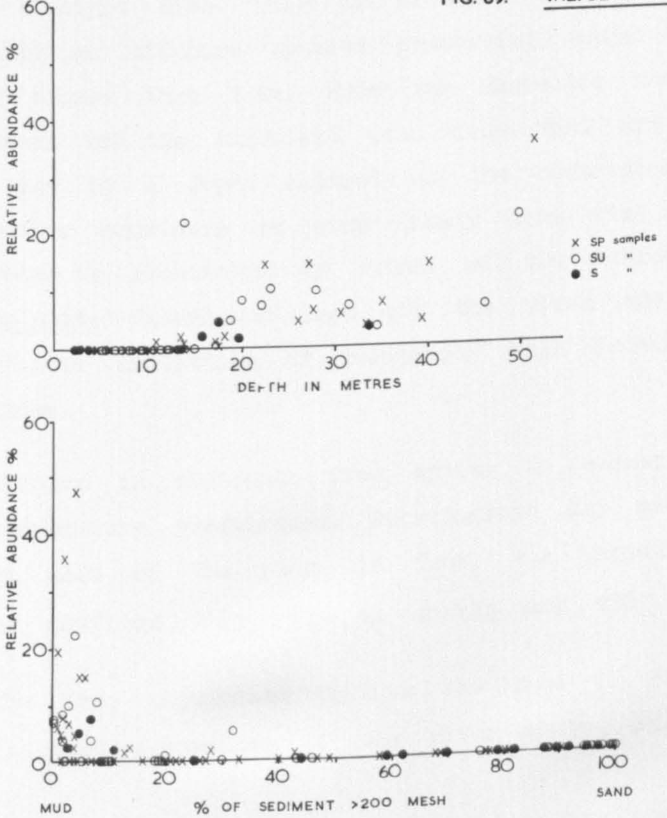


FIG. 69. VALVULINERIA COMPLANATA



Distribution follows the same pattern as in spring with no occurrences in the lagoon, transition or inshore assemblages but with percentages increasing with depth down the pro delta slope. Figure 69 demonstrates that although the mean relative abundance value of the offshore assemblage is approximately the same as in spring, the mean absolute abundance is higher.

V. complanata is found living in depths from 11 to at least 53 m. and it occurs almost exclusively in the muddier grades of sediment. (figure 69). However, there are many stations with a muddy substrate nearer shore where the species does not occur and it is considered that sediment is not the primary factor in determining its distribution. It is interesting to note that the 5 % contour (in figure 68) does not curve around the southern spit into the transition area but continues to the southwest in a straight line. This is probably because V. complanata is basically an offshore species preferring deeper water. It never occurs closer than 1 km. from the shoreline and is probably intolerant of the turbulent conditions that are prevalent inshore. There may be a depth control on the occurrence of the species the author considers it more likely that its shoreward limit of occurrence is restricted by extent of the nearshore turbulent zone. V. complanata flourishes best off the river mouth and obviously must favour conditions of relatively high fertility and rapid sedimentation.

Changes in abundance from spring to summer do not bring out any temperature preferences. Reproduction may occur a constant rate through most of the year; in fact, the proportion of juvenile species confirms this, 12% in spring and 13% in summer.

The dead population follows the trend of the living population with highest occurrences of the river mouth. Also there are few records from the lagoon, transition and inshore assemblages, and percentages increase with depth in the offshore zone. Mean percentages for the assemblages are close to the summer values for the living population and suggest that post - mortem redistribution of the species is not very great.

Recent and fossil occurrences:

D'Orbigny first described the species from the Miocene of the Vienna Basin and the author also has Miocene specimens from this area and also from Marnière de Havrant, Saubrigues, France. It is commonly recorded from the Upper Tertiary of southern Europe and records in Italy go back to the upper Oligocene.

In terms of Recent distribution it appears to be largely a Mediterranean species with records from cores in the Ligurian Sea (Ruscelli 1949) and eastern Mediterranean (Parker 1958). The author has specimens from the Balearic Isles, the Rhône delta and the Bay of Elensis in Greece. In addition, Blanc - Vernet (1963) found it living in the Gulf of Marseille and noted that it was 'fairly abundant' in muds and rare in sands. Outside the Mediterranean it is less common; Colom (1963) recorded it from the estuary of the River Vigo in northwestern Spain. A single specimen was found in a beach sand sample from Jersey in the Channel Islands. This occurrence may represent the northernmost limit of the species as it has not been recorded around the British Isles or farther north.

<u>Asterigerinata</u> sp.

<u>Asterigerinata</u> sp. is a common nearshore species and its areal distribution is illustrated in figure 70. In the spring it

is very abundant at stations close to the shore along the southern delta flank and percentages tend to fall off with increasing depth. It is also abundant around the spit but no specimens were found beyond San Carlos harbour in the lagoon. Highest mean relative and absolute abundance occurs in the inshore assemblage followed by the transition assemblage.

In the summer the living population is considerably reduced; figure 71 demonstrates that both mean relative and absolute abundance values are lower than in spring. However, there is a similar pattern of distribution to the spring with highest abundance nearshore along the southern delta flank and values decreasing with depth. The same pattern is repeated on the northern side of the delta.

Asterigerinata sp. occurs in water of normal salinity within a depth range of 2½ - 27 m. However, it reaches its greatest abundance between depths of 3 and 11 m. (figure 71), and after a peak at approximately 5 m. values tend to fall off with further depth. The sediment / abundance plot in figure 71 shows that the species reaches high abundance in most grades of sediment but that the 'purest' grades of mud appear to be unfavourable. Its pattern of distribution suggests a preference for turbulent conditions such as exist close to the shore along the delta flanks; this well oxygenated environment appears to be much more favourable than the quieter, probably less well oxygenated environment of the lagoons which have a similar depth and a similar substrate in parts.

The higher spring abundance indicates a preference for lower temperatures, certainly lower than the summer mean temperature of 25°C. It is likely that most rapid reproduction occurs early in the year, perhaps early in the spring when temperatures are between 12 and 15°. Following this there is a decrease in the size of

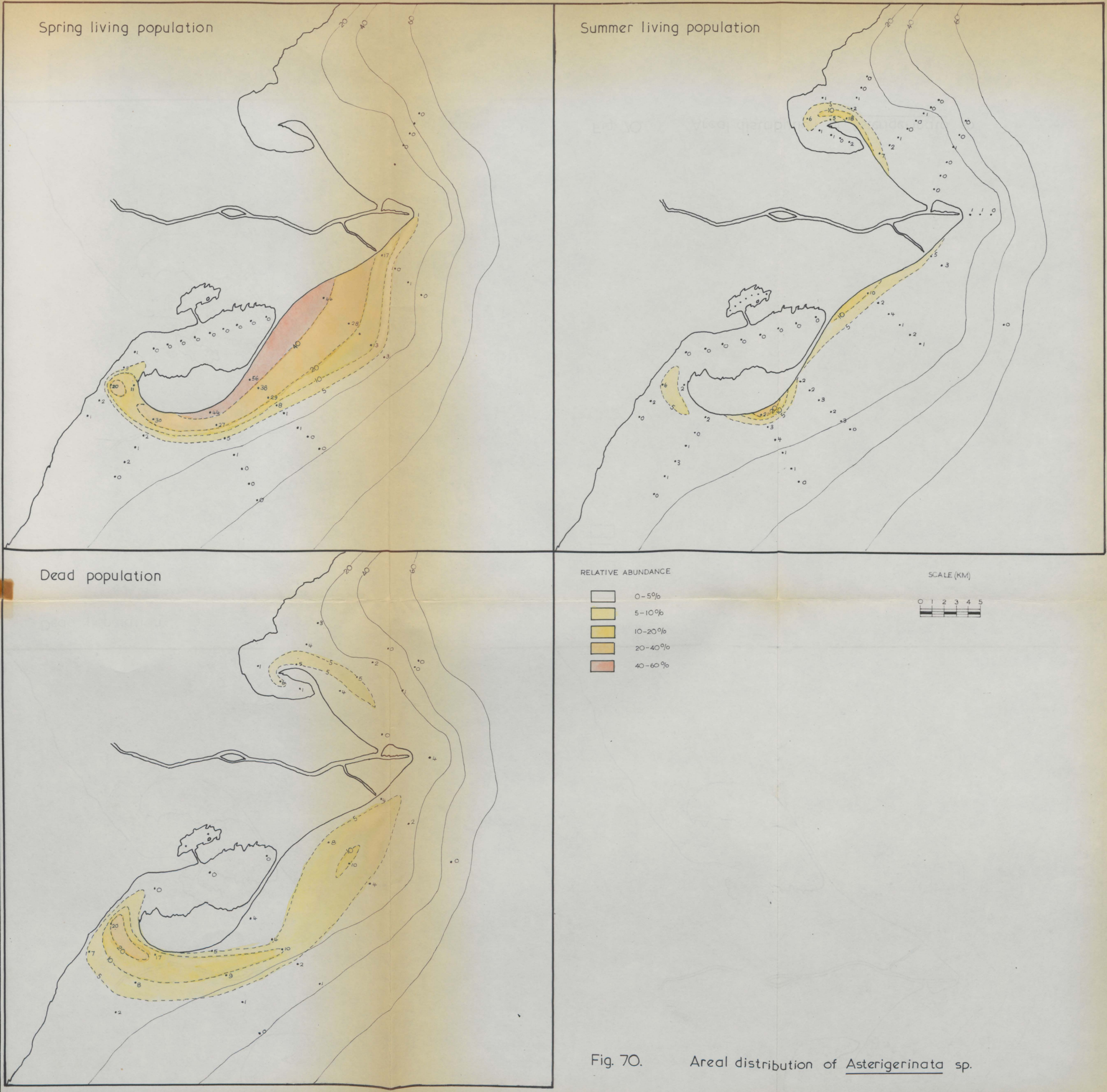


Fig. 70. Areal distribution of Asterigerinata sp.

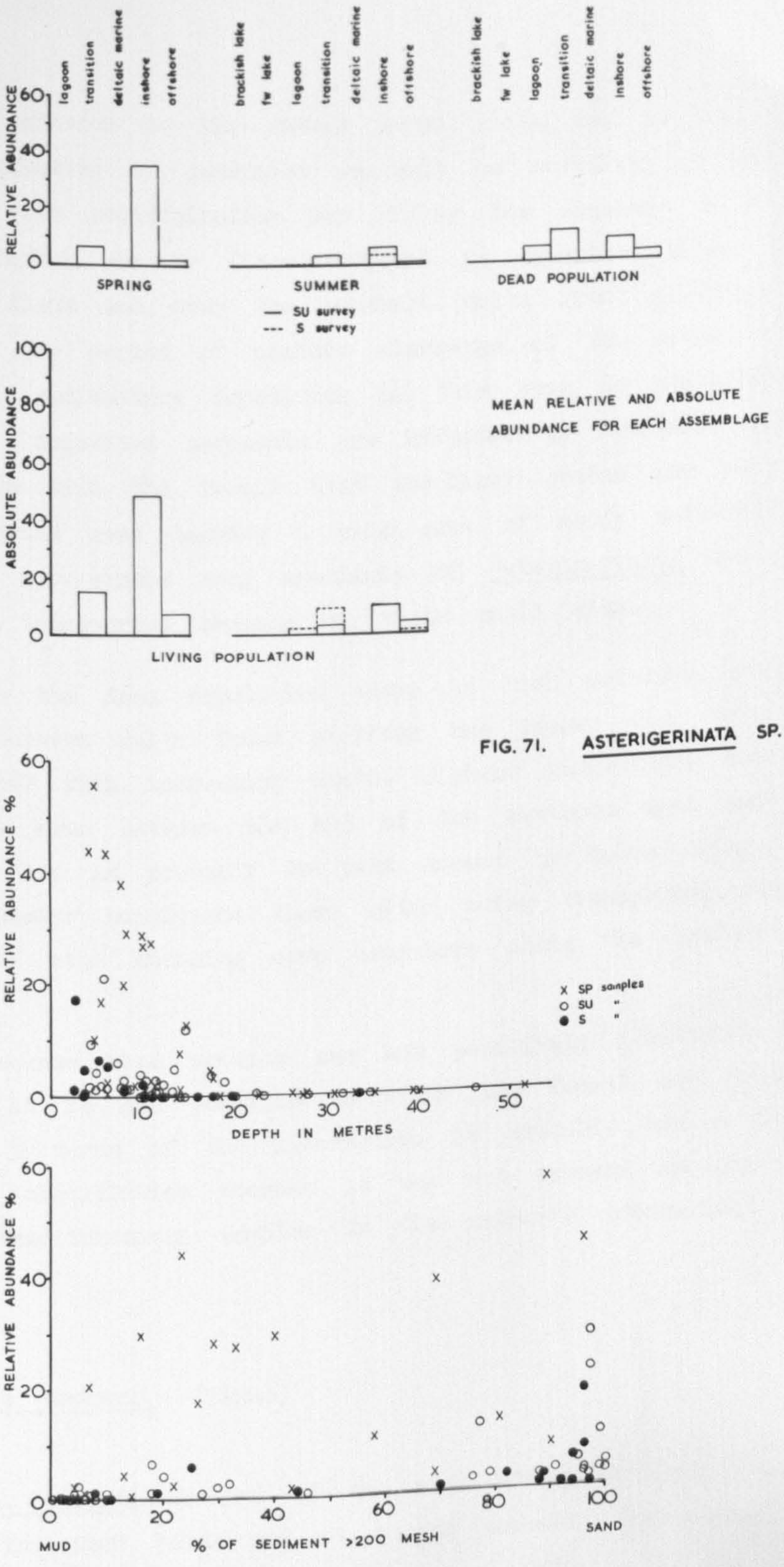


FIG. 71. **ASTERIGERINATA SP.**

the population to the summer level; this may be due to current redistribution of juveniles as well as mortality of older individuals. This redistribution may follow the sequence of sediment distribution whereby finer sediment is deposited along the southern delta flank and over the southern delta front platform in spring during the period of maximum discharge of the river. During the summer, sedimentary deposition in this area is negligible and the spring - deposited sediments are affected by longshore and littoral currents with the result that the finer grades are winnowed and transported away leaving a wide area of sandy sediment. This current action may winnow away specimens of Asterigerinata sp. which are readily transported because of their small size.

In the dead population there is high relative abundance over the southern delta front platform but deeper than 10 - 15 m. values fall off with increasing depth. Highest percentages are recorded in the area between the end of the southern spit and the coastline. This is probably in part caused by tests being deposited in the quieter conditions there after being transported away from the area of high standing crop nearshore along the southern delta flank.

Because this species was not positively identified at species level it is not possible to trace its fossil and Recent distribution by means of the literature. It probably has a restricted modern distribution because it was not present in any of the other Mediterranean samples in the author's possession.

Ammonia beccarii (Linné)

A. beccarii is one of the most widespread and abundant species from the Ebro delta and it occurs commonly in spring and summer

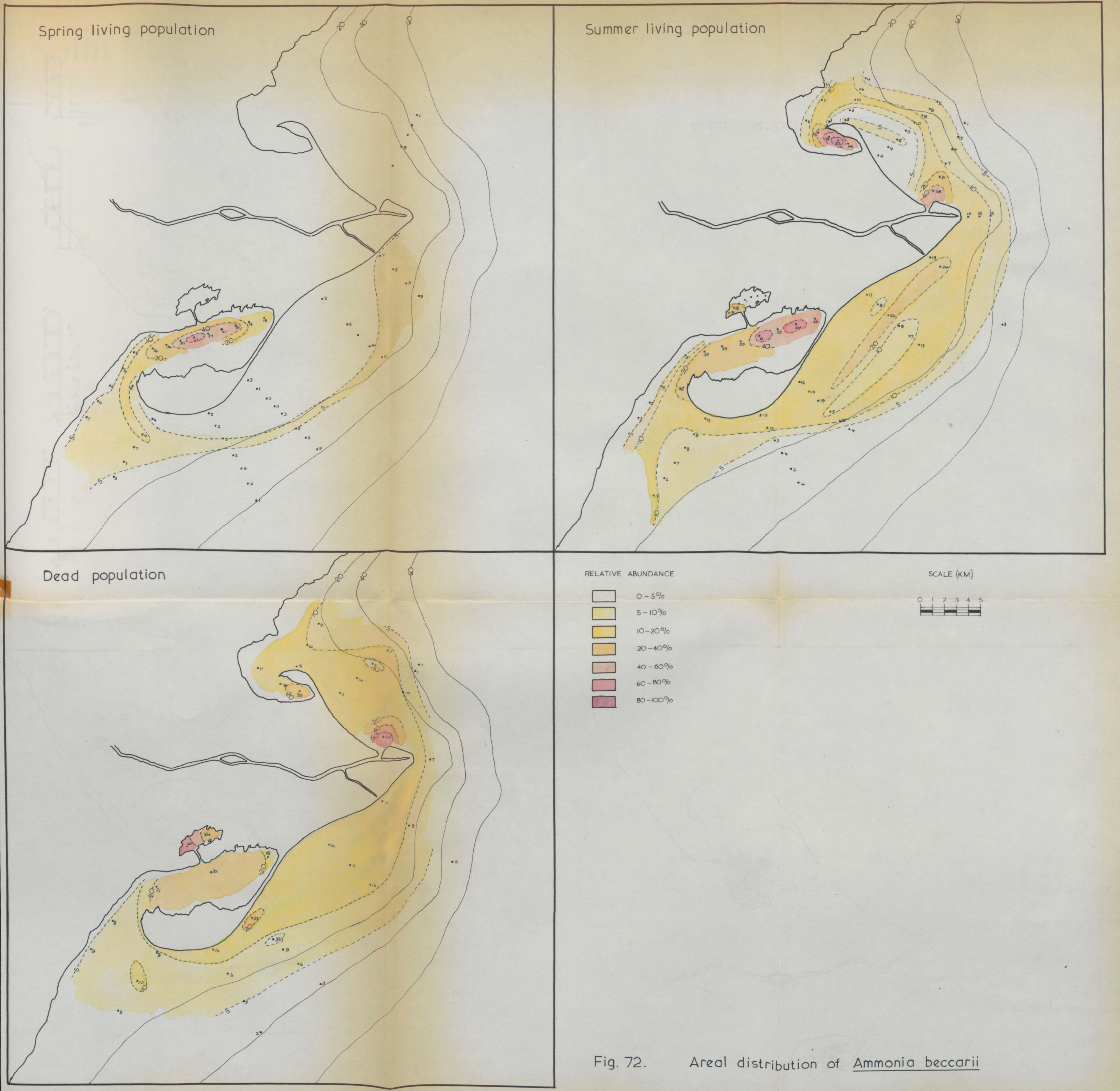
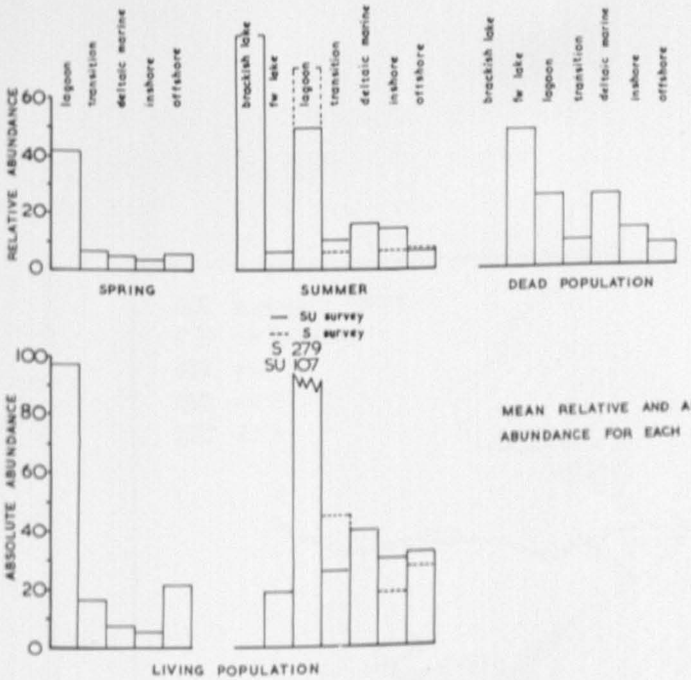
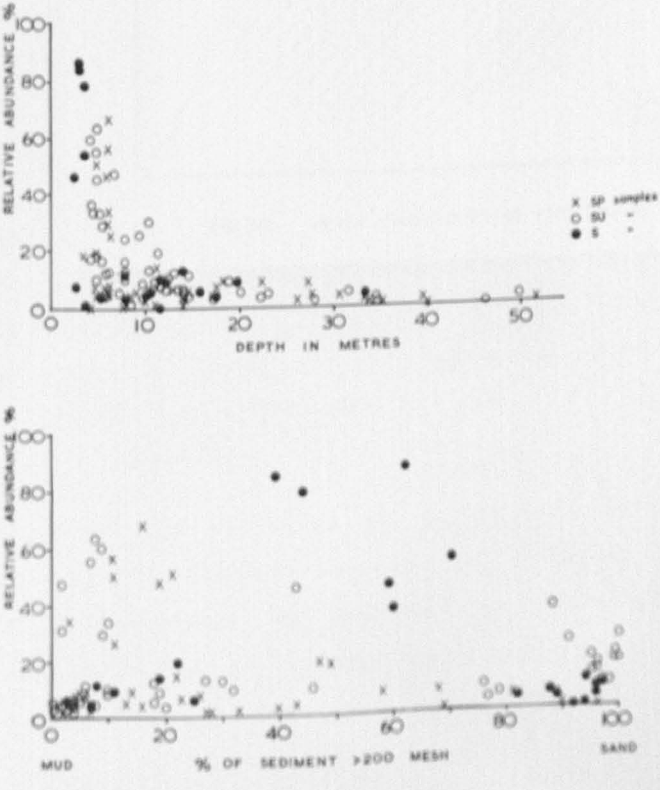


Fig. 72. Areal distribution of Ammonia beccarii



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 73. **AMMONIA BECCARII**



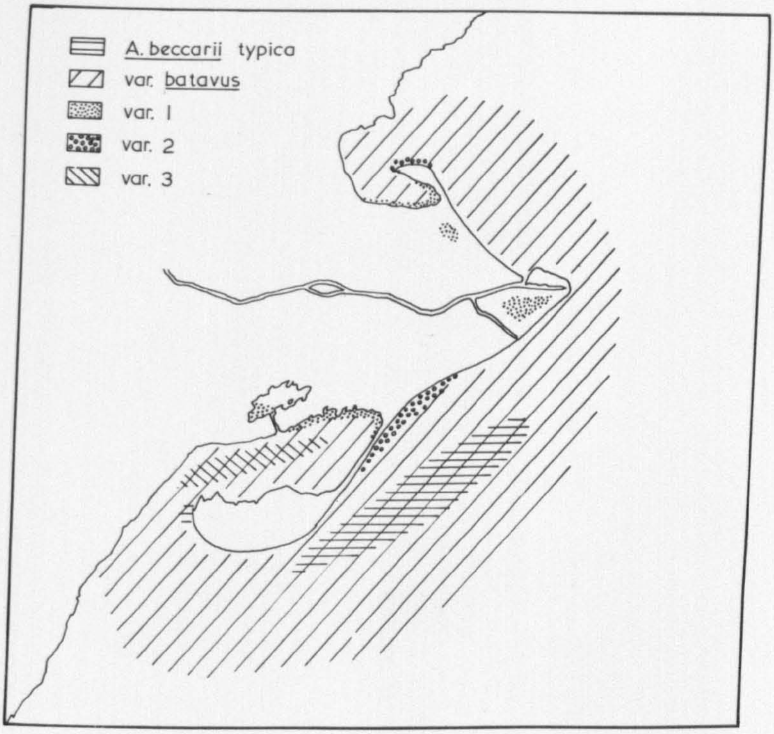


Fig. 74. Areal distribution of varieties of A. beccarii

at all but a few stations. It is widely distributed in marginal marine environments all over the world and has consequently received a good deal of attention from many ecologists.

In the spring high percentages occur in the southern lagoon with highest values in the central area. Elsewhere percentages do not generally exceed 5 % and mean relative abundance values for all assemblages other than the lagoon are close to 5 %. Absolute abundance is again highest in the lagoon followed by the offshore assemblage (figure 73).

In the summer, high relative and absolute abundance is maintained in the lagoons, the northern lagoon having greater abundance than the southern one. There is an all round increase in abundance, each assemblage having higher mean values than the spring. The pattern of distribution changes along the southern delta flank; instead of the spring trend of a gradual increase in percentages with increasing depth to about 20 m. and then a decrease with further depth, there is high abundance over most of the southern delta front platform even close to the shore. Percentages only fall off again at depths greater than approximately 20 m. Relative abundance is not as high over the northern delta front platform but there is high relative abundance at the nearshore stations off the river mouth. A. beccarii is also abundant in the lakes on the subaerial part of the delta; in Encanizada it is present in the western end only but in the brackish lakes it achieves very high abundance.

Each of the varieties of A. beccarii from the Ebro delta has a discrete distribution. It is possible that the species has a different response to different environmental conditions and this is reflected in slight morphological differences. The areal distribution of the varieties is illustrated in figure 74:

A. beccarii typica occurs in an area off the southern delta flank with a predominantly sandy substrate and a depth range of 8 - 15 m. The very small variety (var. 2) is confined to the southern lagoon and is most abundant in the western part. Var. 1 is found in water of below normal salinity, chiefly in the brackish lakes, Encanizada, and the margins of the two lagoons where there is dilution of seawater with freshwater from the numerous drainage channels running off the delta. Var. batavus is the most common variety and is distributed throughout the normal marine environments although it shows considerable variation of form itself. Var. 3 is found in very small numbers at several nearshore stations but is most abundant close to the shore off the northern spit and nearshore off the southern delta flank.

The dead population follows approximately the same pattern of distribution as the summer living population. There is high relative abundance close to the shore along the delta flanks and extending over the delta front platforms. After about 15 - 20 m. abundance falls off with further depth. There is a localized high off the mouth of the river and consistently high percentages in the lagoons and the western part of Encanizada. The mean percentages for the various assemblages are approximately the same or slightly lower than the equivalent values for the living populations with the notable exception of the deltaic marine assemblage. The distribution of the dead population is sufficiently similar to the living population to suggest that there is probably little post - mortem transport of empty tests of A. beccarii.

From the field evidence it appears that A. beccarii is most successful in the semi - enclosed environment of the lagoons rather than in open marine areas. The abundance / depth plot in figure 73 illustrates that it prefers shallow water; it is found in depths from a few centimetres to at least 53 m. but is only abundant less than 10 m. It is obviously a very hardy species being extremely abundant in the turbulent conditions of the delta front platform and off the river mouth. It is also tolerant of a wide range of salinity. In the western part of Encanizada, for instance, it reaches up to 28 % of the population in salinity of around 4 °/oo. However, it is absent from the eastern part of Encanizada where salinity is lower still. High percentages are recorded in salinities ranging from 4 - 39 °/oo but the species is consistently most abundant under the conditions of normal salinity that occur in the lagoons.

A. beccarii is also tolerant of a fairly wide range of temperatures. It is abundant in spring when sea temperatures are 13 - 15°C and also in summer when temperatures reach 25 - 28°. In some of the shallow lakes on the subaerial part of the delta it is found living in temperatures exceeding 30°. However, increased abundance in the summer suggests that it favours the warmer temperatures and that some stage during the early summer temperatures reached a level that encouraged relatively rapid reproduction. An average of 9 % of all individuals of A. beccarii in each of the spring samples were juveniles (juvenile - taken as having less than one complete whorl of chambers) whereas 17 % were juveniles in the summer surveys. This indicates that reproduction probably takes place during the spring only at a slow rate but as temperatures rise during the summer so does the rate of reproduction resulting in a larger proportion of juvenile specimens and a larger standing crop.

The sediment / abundance plot in figure 73 demonstrates that A. beccarii is found in all grades of sediment and therefore has no preference for a particular type of substrate. The optimum conditions for A. beccarii as observed from the Ebro delta can be concluded as being a sheltered, nearshore environment with water of normal salinity and depth less than 10 m. and temperatures exceeding 25°C.

A. beccarii is one of the few species on which ecological experiments have been carried out in the laboratory. Bradshaw (1955, 1957 and 1961) carried out a series of experiments to determine the ecological tolerance limits of the species. He found that there was no growth in temperatures below 10° or above 35° and although specimens could survive indefinitely below 10°, prolonged exposure to temperatures above 35° resulted in death. No reproduction occurred below 18° and the optimum temperatures for reproduction were between 25 and 30°. A. beccarii was also found to be tolerant of low salinities but reproduction and growth were very slow below 15 ‰ and were highest at a normal salinity of 34‰.

The Ebro delta field observations tie in very well with Bradshaw's laboratory results. Reproduction is higher in the summer because temperatures are then within the optimum for reproduction as determined by Bradshaw. However, reproduction does occur around the Ebro delta in spring (because many juvenile specimens were observed) when temperatures are below Bradshaw's experimental minimum for reproduction. Also, there are a few localities, notably the brackish lakes, where high percentages of A. beccarii occur in water of very low salinity. It is likely that the salinity in these situations is not consistently low but variable; freshwater influx from the drainage channels would lower the salinity whereas in hot weather evaporation would raise it. At some stage in the summer, salinity conditions would be suitable for rapid reproduction.

Bradshaw observed that A. beccarii is very tolerant of extreme pH values. This is interesting because around the Ebro delta it is the dominant species where there is a high organic content in the sediment. Both the lagoon and the nearshore stations off the river mouth were observed to have high organic contents in the sediments resulting in an acid substrate. Other species are probably not as tolerant of pH variation as A. beccarii and so it may be able to flourish in these environments at their expense.

Recent and fossil occurrences:

A. beccarii has a very wide distribution in nearshore environments and can be said to be truly cosmopolitan. Phleger (1960) said that it "is one of the most abundant typical forms of lagoons and nearshore areas where the environment may be characterized as being more variable than in most other places".

Records of the species extend well back into the Tertiary and Brooks (1967) said that it has been found in deposits as old as late Cretaceous. Curry et al. (1965) found var. batavus in sediments of Aquitainian age from the Western Approaches of the English Channel. They also recorded it from the Vindobonian and the author has specimens of Helvetian age from Saubrigues in France. Other records come from the Miocene of the Vienna Basin and it is common in Pliocene and Pleistocene samples from all over Europe; for example, samples taken by the author from the Chillesford Beds (Pleistocene) of Suffolk are dominated by A. beccarii.

Living representatives of A. beccarii are found all over the world, particularly in temperate and warm temperate waters. There are records from the Australian, Pacific and South American regions and it is widely distributed through the Mediterranean, Red Sea, Persian Gulf and along the coastline of Europe. Macfadyen (1940) observed that the northern limit of the species was the Faröe Islands and Murray (1968) noted that on the western side of the Atlantic it is rare north of Cape Cod.

Many records come from the North American coastal area; Bandy

(1953) considered it to be the diagnostic species for the brackish zone off the coast of California. Phleger and Lankford (1957) discovered that A. beccarii was very abundant in bays along the Texas coast where the temperature range of 15 - 30° is similar to that of the Ebro delta. With salinites of 2 - 33°/oo they considered that conditions were close to the optimum for the species. Lankford (1959) in his study of the foraminiferids of the eastern part of the Mississippi delta also found that A. beccarii is very abundant. He reported that it is most abundant in the Sound facies which is roughly equivalent to the Ebro lagoons (being semi - enclosed by barrier islands, having a depth of 1 - 9 m., salinity between 18 and 36 °/oo and temperatures between 15 and 30°). In the less saline environments, such as the Interdistributary bay and Deltaic marine facies, it is generally less abundant.

Blanc - Vernet (1958) and Kurc (1961) noted that A. beccarii is the dominant living species in the Etangs along the French Mediterranean coastline. Murray (1961) found that although A. beccarii from Christchurch Harbour were able to tolerate very low salinities there was evidence that the species is stenohaline, prefering more stable, higher salinities. He also suggested that the low temperatures of Christchurch Harbour mean that the species is living close to its lowest temperature tolerance. Brooks (1967) undertook a detailed study of standing crop, vertical distribution and morphometrics of A. beccarii from an area in Naragansett Bay. He found no statistically significant difference in population size from month to month throughout the year and that the species is infaunal as well as epifaunal, living down to at least 4 cm. depth in the sediments.

The short review above covers only a small part of the wealth of published ecological information concerning A. beccarii. Its cosmopolitan distribution has resulted in it being a major species in the faunas of most sediment samples taken in marginal marine environments from many parts of the world. It is basically a warm temperate species flourishing best in temperatures of more than 25°. It appears to prefer a shallow water lagoonal or near-shore type of environment and can live within a wide range of salinity although it is most abundant in higher salinities. These optimum conditions occur around the Ebro and Mississippi deltas and in several Texas Bays and A. beccarii is consequently very abundant. Bradshaw's ecological experiments on the species confirmed these field observations and in this case points to the value of laboratory studies on living foraminiferids.

Elphidium c.f. E. flexuosum (d'Orbigny)

In the spring E. c.f. E. flexuosum is abundant only within a restricted area extending from the Vinaroz traverse to the southernmost stations in the Las Casas traverse (figure 75). Increasing percentages to the south of this small area suggest that the area of high abundance may extend farther south parallel to the coast. The species is not recorded in the southern lagoon and elsewhere there are a few isolated occurrences, chiefly in the offshore assemblage. In the summer the spring 'high' has disappeared and there are only a few individuals recorded from the whole deltaic area.

Figure 76 demonstrates that E. c.f. E. flexuosum is found living in depths from $8\frac{1}{2}$ - 28 m. although it is only abundant within a range of 9 - 13 m. and that it has a preference for muddy sediments. There are, however, many stations with a muddy substrate and shallow water where the species is absent and it seems likely from the distribution pattern that it is not typically

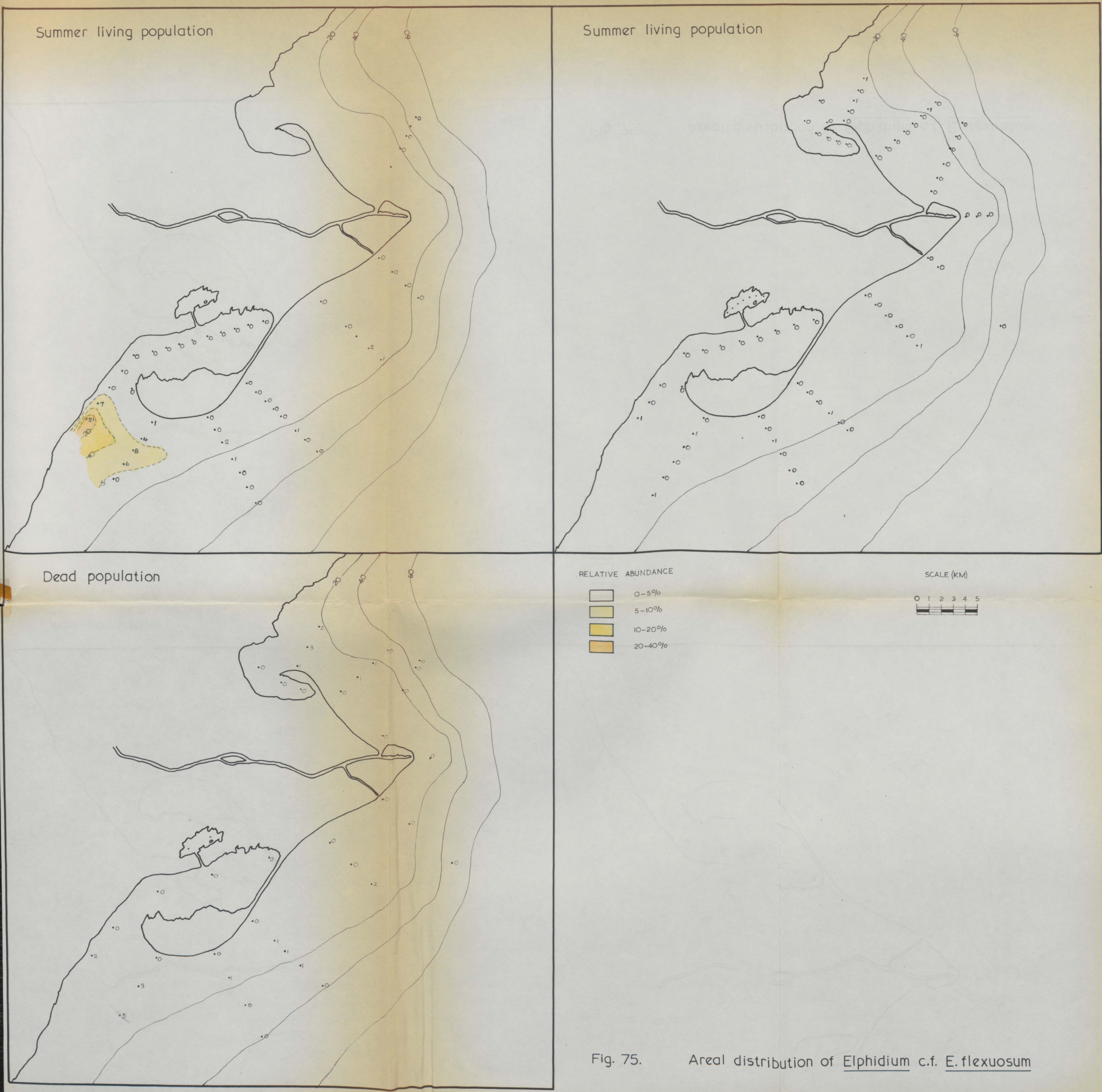
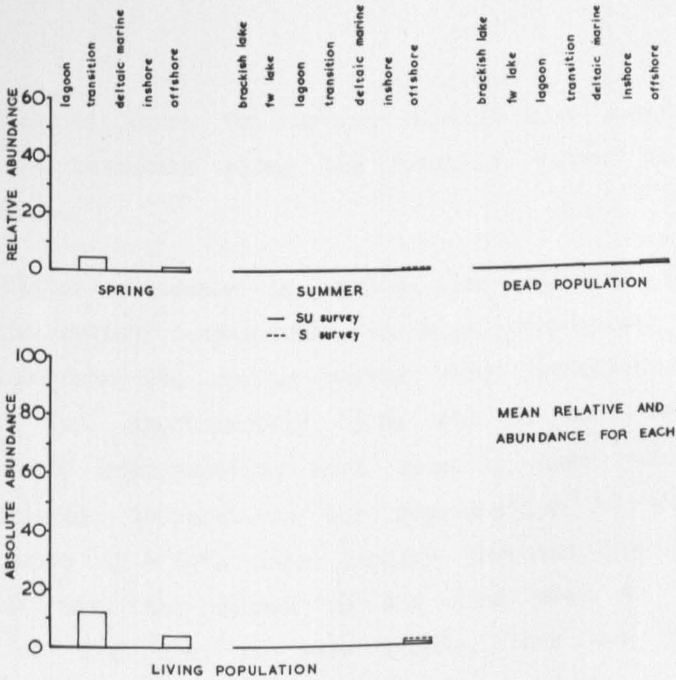
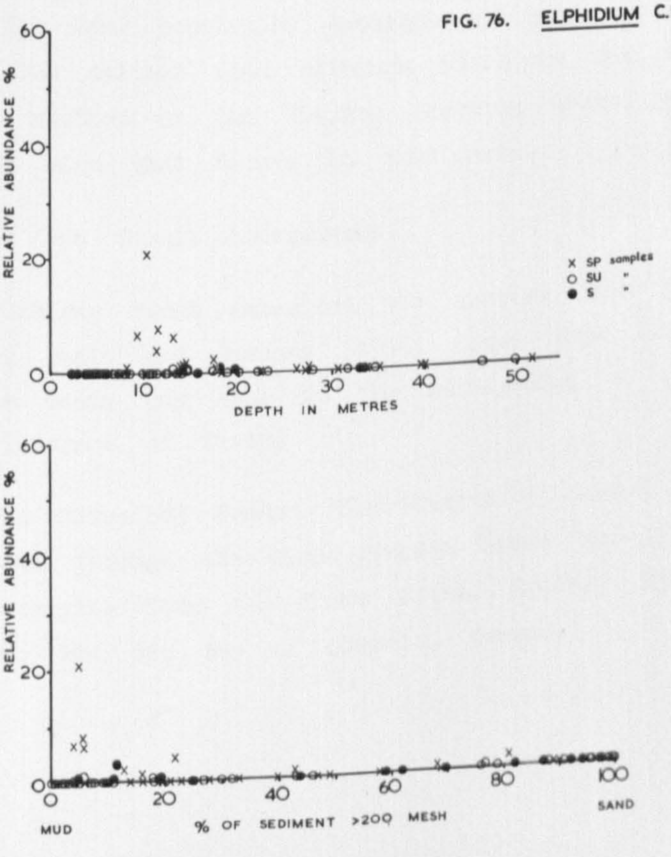


Fig. 75. Areal distribution of Elphidium c.f. E. flexuosum



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 76. **ELPHIDIUM** C.F **E. FLEXUOSUM**



a 'deltaic' form. The spring distribution suggests that it is abundant nearshore along the 'normal' rather than the deltaic coastline.

Higher abundance in spring also suggests that the species prefers cooler temperatures. A high proportion of the individuals counted from the spring survey were juveniles (see plate 16, figure 1a), approximately 65 %, and it must be concluded that a period of reporoduction must recently have taken place and that the optimum temperatures for reproduction in this species are in the range 12 - 14°. This largely juvenile population does not persist into the summer in the same area to become adult; either most of them die, or more likely, they are transported southwards by currents.

The dead population consists of only isolated occurrences all over the deltaic area although there is one value of 5 % at the final station on the Vinaroz traverse which partially reflects the spring high that occurs in that area.

Recent and fossil occurrences:

D'Orbigny first described the species from the Miocene of the Vienna Basin and Cushman (1939) noted that it is common in the Vienna Basin and also in the Burdigalian of Gironde, France, and the Pliocene of Italy.

In terms of Recent distribution it seems to be widely distributed through the Mediterranean area; the author has specimens from samples from the Rhône delta, Naples, the Balearic Islands, Tripoli and the Bay of Elensis, Greece.

Elphidium lidöense Cushman

This species has low abundance in the spring. The areal distribution map (figure 77) shows that it is absent from the southern lagoon and from the river mouth area. Elsewhere percentages are generally low and the highest figure of 5 % is recorded along the Las Casas traverse.

It is much more common in the summer, both in terms of relative and absolute abundance. It is still rare in the lagoons but elsewhere four distinct highs are apparent. Within the deltaic marine assemblage there is high relative abundance in the stations nearest the river outlet and this may be continuous with the high value at the end of the Cabo Tortosa traverse. The second high is towards the edge of the southern delta front platform. The remaining two highs are situated just off the ends of the two spits. E. lidöense has highest mean relative and absolute abundance values in the offshore assemblage followed by the deltaic marine assemblage, but its distribution is more associated with the localized highs rather than being distributed evenly through a particular environment.

The sediment / abundance plot in figure 78 demonstrates that although highest percentages of E. lidöense occur chiefly in muddy sediments it is by no means altogether confined to these; it can apparently also live in sandy sediments. However, it does appear to be more particular about the depth in which it lives. The abundance / depth plot illustrates that it has an overall depth range of 4 - 40 m. but only becomes abundant within a very narrow range of 6 - 15 m.

Abundance is considerably greater in the summer compared to the spring and it must be concluded that E. lidöense flourishes better in warmer temperatures. The species had obviously undergone,

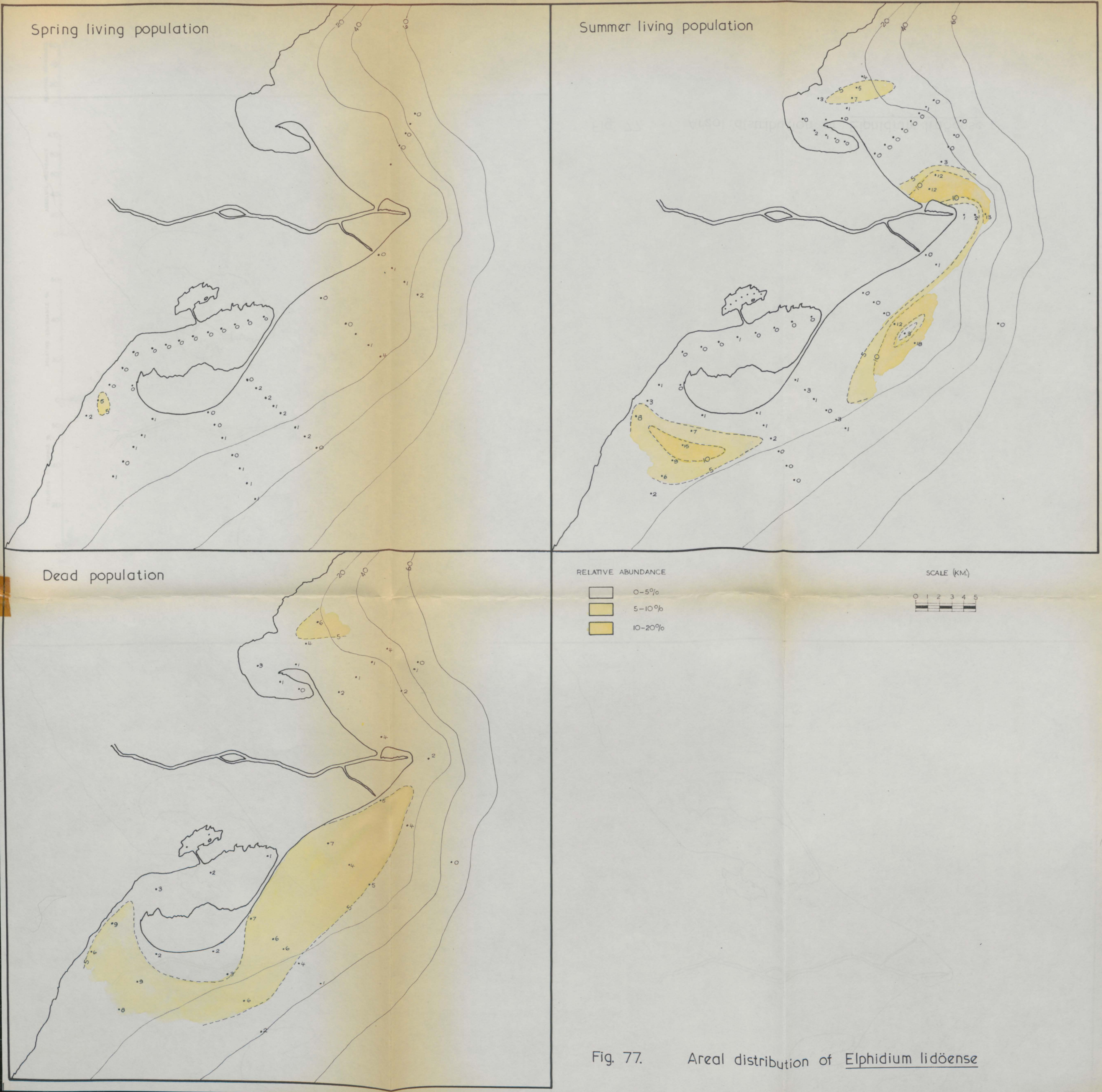


Fig. 77. Areal distribution of Elphidium lidöense

(1958) collected specimens from the Celtic Sea.

Elphidium selseyensis Heron - Allen and Earland

E. selseyensis is rare in the spring and never attains more than 1 % of the living population at any station. In the summer both relative and absolute abundance are considerably increased. The species is absent from the southern lagoon but there are a few individuals in the northern lagoon. Elsewhere there are three distinct areas of high relative abundance: one area is off the northern spit extending into the transition area, another is off the southern spit and the remaining one is towards the edge of the central part of the southern delta front platform (figure 79). Its distribution pattern closely follows that of E. lidöense being not related to particular assemblages but rather to localized areas of high abundance.

E. selseyensis is found within a depth range of 2½ - 40 m. but is only abundant within a very narrow range, 6 - 17 m. (figure 80). It is found through all grades of sediment except the 'purest' sands and muds (see sediment / abundance plot, figure 80). Increased abundance in summer suggests an early summer period of reproduction and a preference for warmer temperatures. These features are also common to E. lidöense and there appears to be a strong association between the two species. The factors determining their distribution are difficult to ascertain but each has its maximum abundance within a very narrow depth range and in localized areas that do not relate to any particular set of ecological conditions.

The distribution of the dead population does not reflect the distribution of the living population to any great extent. This is unusual because E. selseyensis is a very large species and one

(1958) collected specimens from the Celtic Sea.

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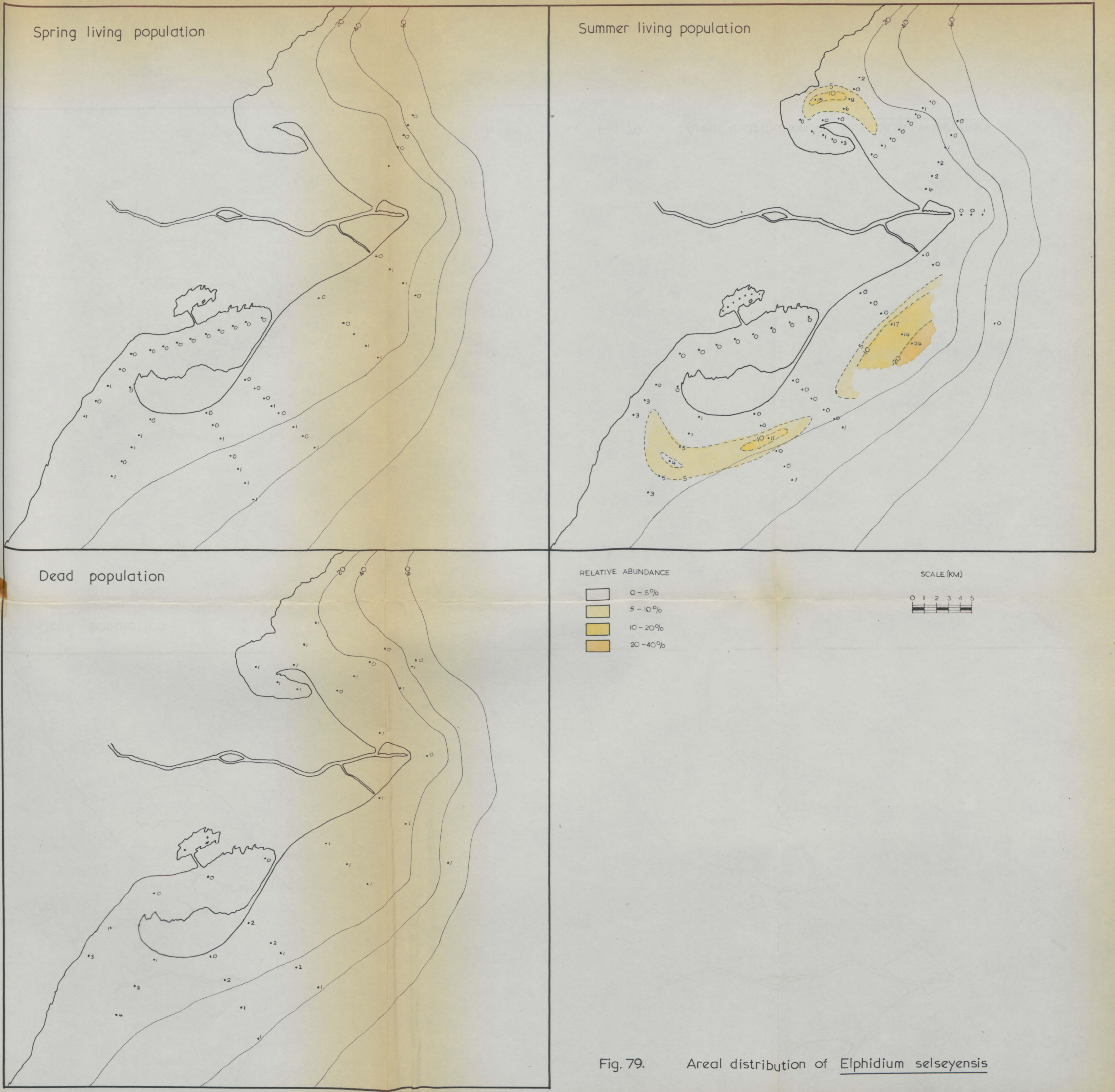
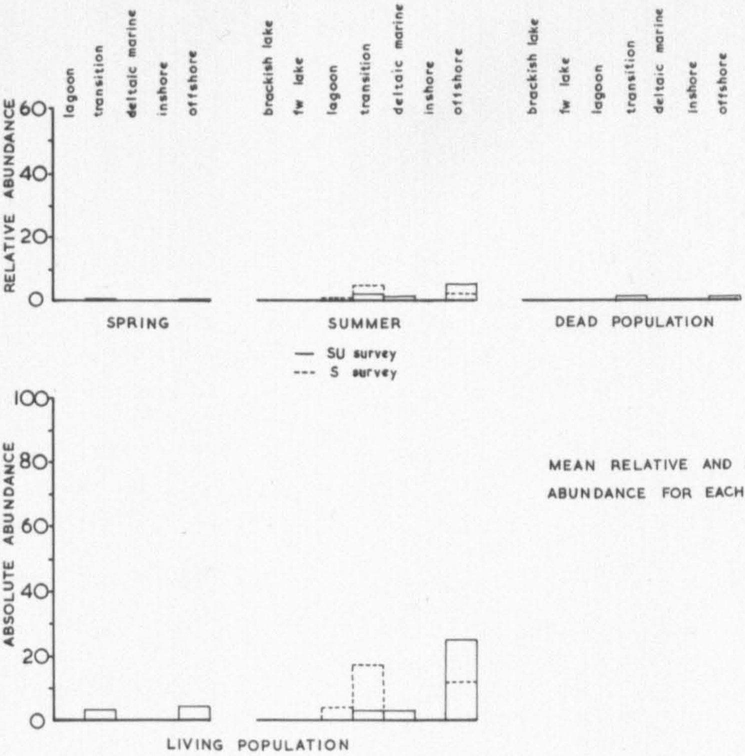
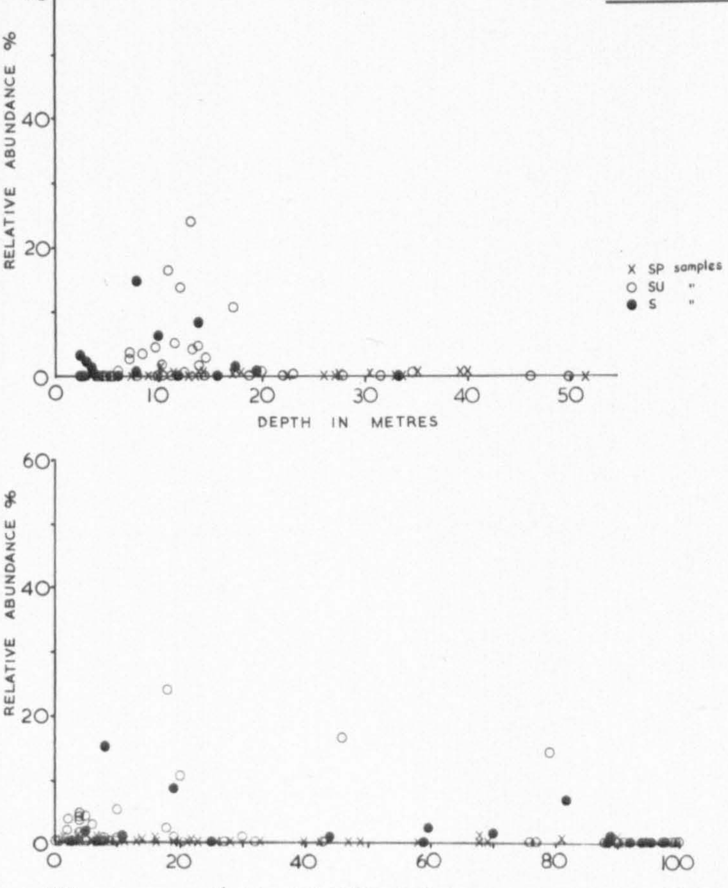


Fig. 79. Areal distribution of Elphidium selseyensis



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 80. ELPHIDIUM SELSEYENSIS



would expect that it would be correspondingly less susceptible to redistribution by currents. Nevertheless, relative abundance is generally lower than for the summer living population but not as low as in spring. The highest percentages are found south of the southern spit which partially reflects the high that exists there in the summer.

Recent and fossil occurrences:

E. selseyensis is basically a Recent species although Fehling-Hansen (1954) recorded it in 'transitional sediments' from an Arctic clay of Pleistocene age near Oslo.

The type specimens were obtained off Selsey Bill and the species is common throughout the English Channel area. The author also has specimens from Brittany, the Rhône delta and Rimini. Haake (1967) recorded it in the Baltic Sea and Cushman (1939) said that it had been recorded much farther afield from the Kerimba Archipelago and the Antarctic.

Elphidium sp. 1

In the spring _Elphidium_ sp. 1 is most abundant off the southern spit in an area extending from the Vinaroz traverse to the Las Casas traverse. It is absent from the lagoon and deltaic marine assemblages but in most other assemblages it is present in small numbers (figure 81).

In the summer the spring high is no longer apparent but there is a small high at about 20 m. depth on the Salinas traverse. Off the river mouth there is a considerable increase in abundance and there is also another small high at about 20 m. depth off the

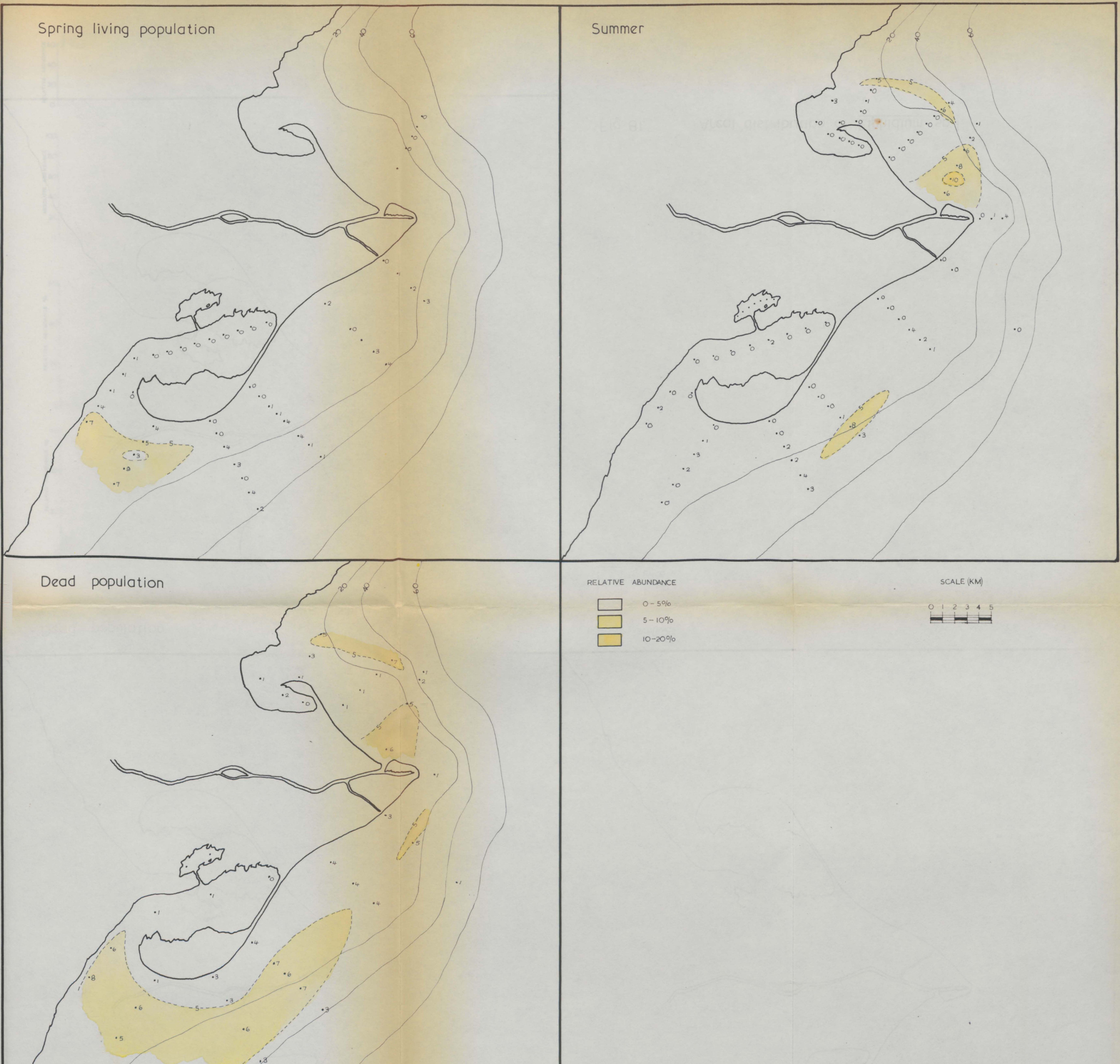


Fig. 81. Areal distribution of Elphidium sp. 1.

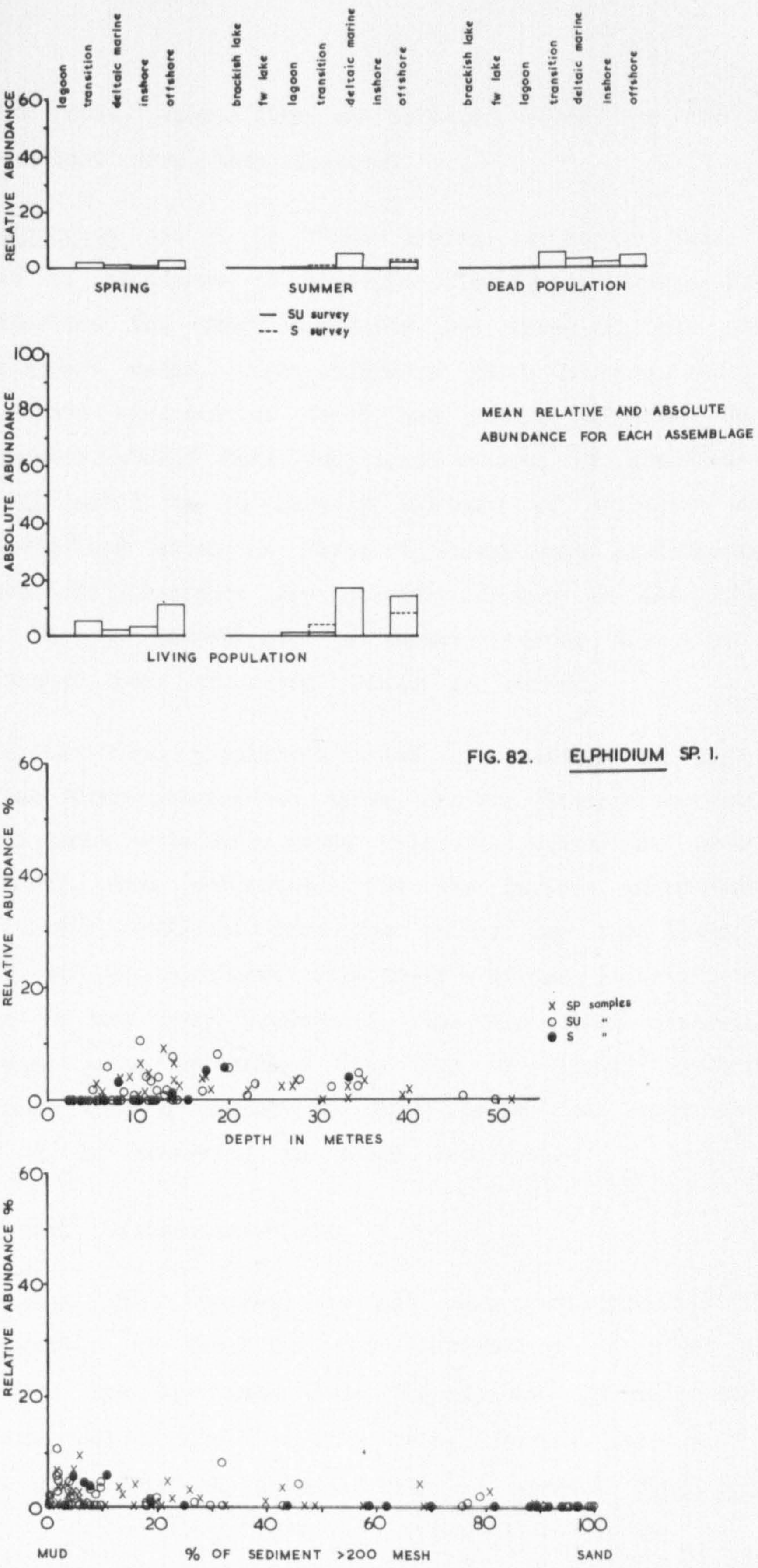


FIG. 82. ELPHIDIUM SP. 1.

northern spit. Apart from an isolated record in the south, E. sp. 1 is absent from both lagoons.

Elphidium sp. 1 is found living in depths from 5 - 40 m. with a peak of abundance at approximately 12 m. (figure 82). It has a preference for muddy sediments but lives in all grades except the cleanest sands. High abundance shows no consistent correlation with either sediment or depth and it is difficult to know why the species should have localized centres of abundance where it does. It seems to be equally tolerant of turbulent and more quiet conditions and shows no distinct temperature preferences. Relative and absolute abundance are slightly higher in the offshore and deltaic marine assemblages in summer whereas the other assemblages have higher mean abundance values in spring.

In the dead population there are centres of high relative abundance corresponding to those of the living population: off the southern spit extending round into the transition area and off the river mouth. Mean percentages for the various assemblages are not significantly different from the values for the living population and it can be concluded that post - mortem redistribution of the species is not very pronounced. The transition areas, however, have a higher mean percentage than for the living population and it is likely that a number of empty tests are swept along the delta flanks to be deposited in these two areas.

Recent and fossil occurrences:

Because this species has not been satisfactorily identified it is impossible to determine its distribution in other areas. However, the author has specimens from the English Channel area, Brittany, the Rhône delta, the Balearic Isles, Venice Lido and the Bay of Naples. From this it appears that at present Elphidium sp. 1 is widely distributed through the northwestern Mediterranean (it is absent from samples examined from the eastern Mediterranean) and the English Channel area.

Protelphidium anglicum Murray

P. anglicum occurred in very few of the stations sampled at either season; it is restricted largely to brackish water environments. No such environments were sampled in the spring survey so there are no records of the species for the spring.

In the summer it is found in the eastern end of the northern lagoon but not at all in the part of the southern lagoon sampled. There is very high abundance in Encanizada; at the western end of the lake it is accompanied by smaller numbers of Ammonia beccarii but in the central and eastern parts it constitutes 100 % of the living population. It is also found in many other small, shallow lakes over the delta but never reaches the high abundance that it attains in Encanizada.

Plots of abundance against depth and sediment grade (figure 84) show that P. anglicum lives within a depth range of a few centimetres to at least 3 m. and in a whole range of sediment grades. The effects of temperature on P. anglicum cannot be gauged because the environments in which it lives were only sampled at one season. However, it seems to flourish in the warm summer temperatures: 28^{o} in Encanizada and often more than 30^{o} in some of the shallow brackish lakes.

The chief factor governing the distribution of this species is the salinity of the water. It is found in salinities ranging from 0.6 to 38 $^{o}/oo$ but its highest abundance is in Encanizada

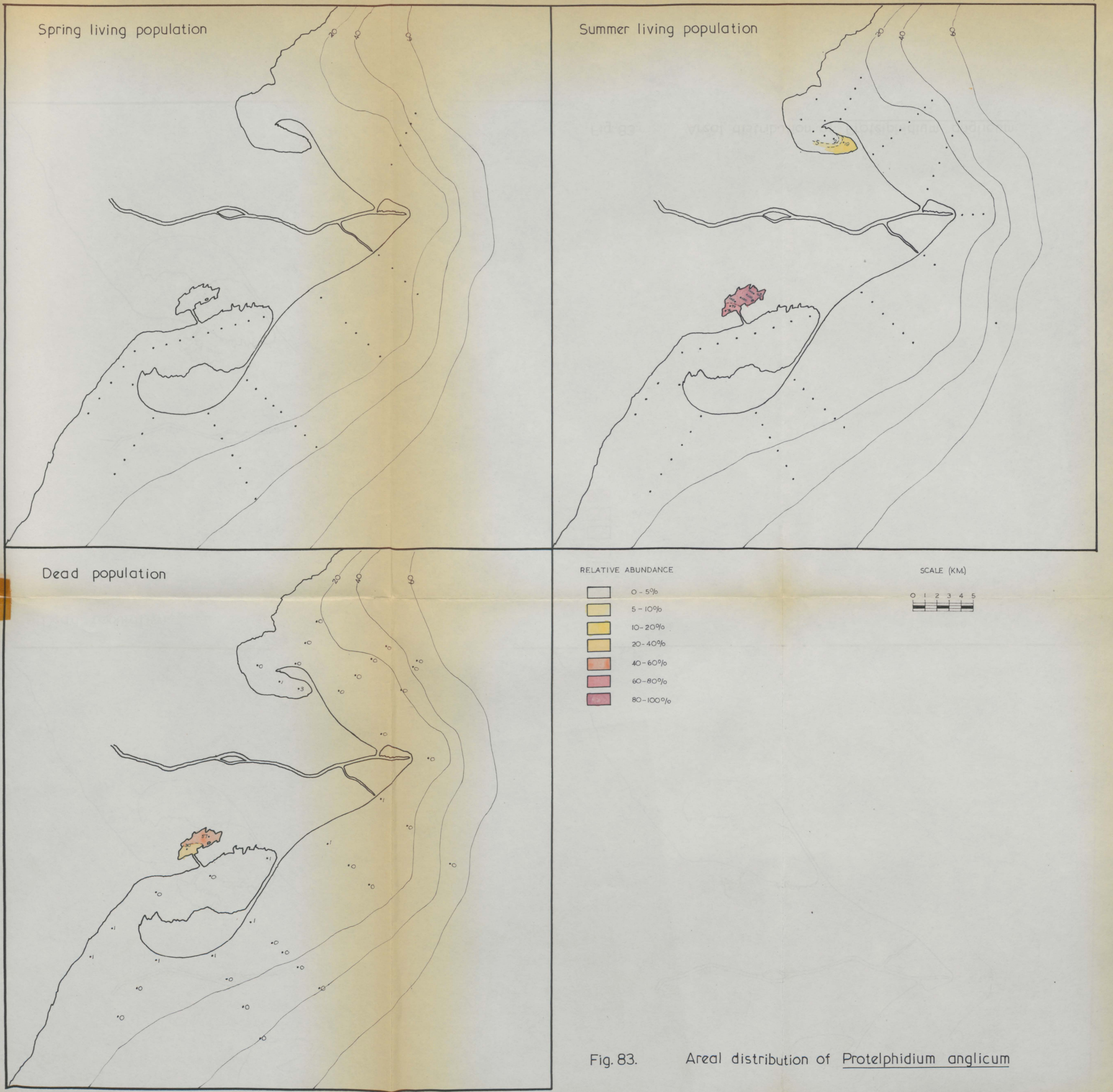
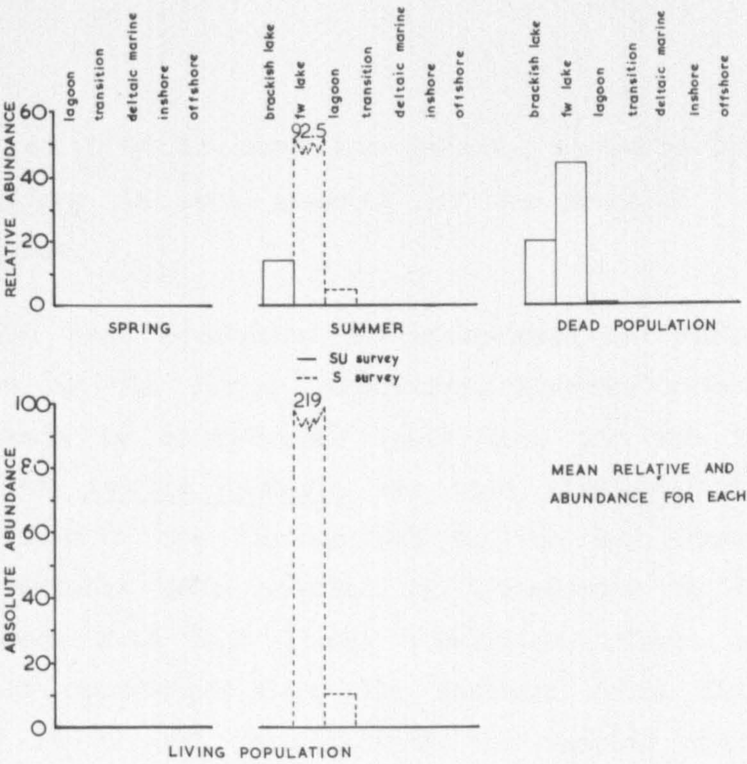
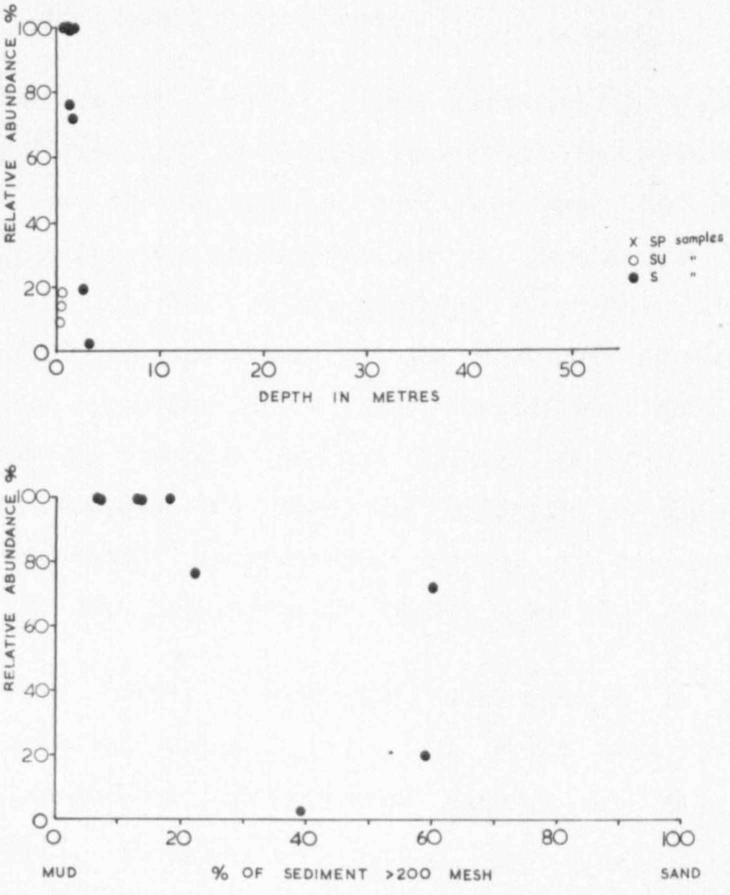


Fig. 83. Areal distribution of Protelphidium anglicum



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 84. **PROTELPHIDIUM ANGLICUM**



where salinity is very low indeed, virtually freshwater conditions. P. anglicum is less abundant in the brackish lakes where salinity is higher.

The dead population is distributed in virtually the same pattern as the living population. However, relative abundance in Encanizada is considerably lower than for the living population; tests of Ammonia beccarii are more abundant. There are a few occurrences in the lagoons and on the Las Casas traverse; tests have probably been reworked or transported to these areas from the areas with high living populations. There are also a few isolated occurrences along the southern delta flank close to the shore. It is not thought that the species ever lived in this environment; the specimens have probably been reworked from older deposits during the erosion of an old delta apex.

Recent and fossil occurrences:

When Murray (1965b) first described P. anglicum he stated that many authors had previously referred the species to Nonion depressulus. Because of the widespread confusion over the nomenclature with N. depressulus it is impossible to derive the present day and fossil distribution of P. anglicum from the literature. The author could find no specimens in any Tertiary samples in his possession with the exception of a late Pleistocene sample from the Severn Estuary. The species is not present in any of the modern Mediterranean samples but then the majority of these samples are not from 'subaerial' environments and so it may well occur in other parts of the Mediterranean apart from the Ebro delta.

Murray (1961) stated that the species is common all around the coasts of Great Britain. He found that it was the most common species in Christchurch Harbour and added, "It is quite clear that, although P. anglicum will live in a normal marine environment, it is never particularly successful there and forms only a minor element of the population. Presumably its successful colonization of an area is largely dependent upon the fact that the area should be unfavourable for the development of its competitors". He also noted its abundance in samples taken from the Wash and concluded that P. anglicum appears to be a euryhaline, eurythermal and eurycalcine species capable of living in areas of low pH and high wave action and exposure to the atmosphere at low tide. Conclusions on the ecology of the species around the Ebro delta are largely in agreement with these observations.

Nonion depressulus Walker and Jacob emend. Murray

In the spring the highest percentages of N. depressulus are found in the 20 - 25 m. depth range southeast of the southern spit and in a second area nearshore on the southern channel traverse. There is also one high value in the northeastern corner of the southern lagoon but other lagoon values are low and the species is absent altogether from the western part. It is common in open marine areas in both inshore and offshore assemblages but decreases in abundance in the deeper water stations. Although the inshore assemblage has highest mean relative abundance, the offshore assemblage has highest absolute abundance.

The pattern of distribution changes appreciably in the summer (areal distribution map figure 85). The species is still absent from the western part of the southern lagoon but abundance is increased in the eastern part. The high southeast of the southern spit has disappeared and most stations around the spit show a marked decrease in relative abundance. However, farther north off the southern delta flank, abundance is high close to the shoreline

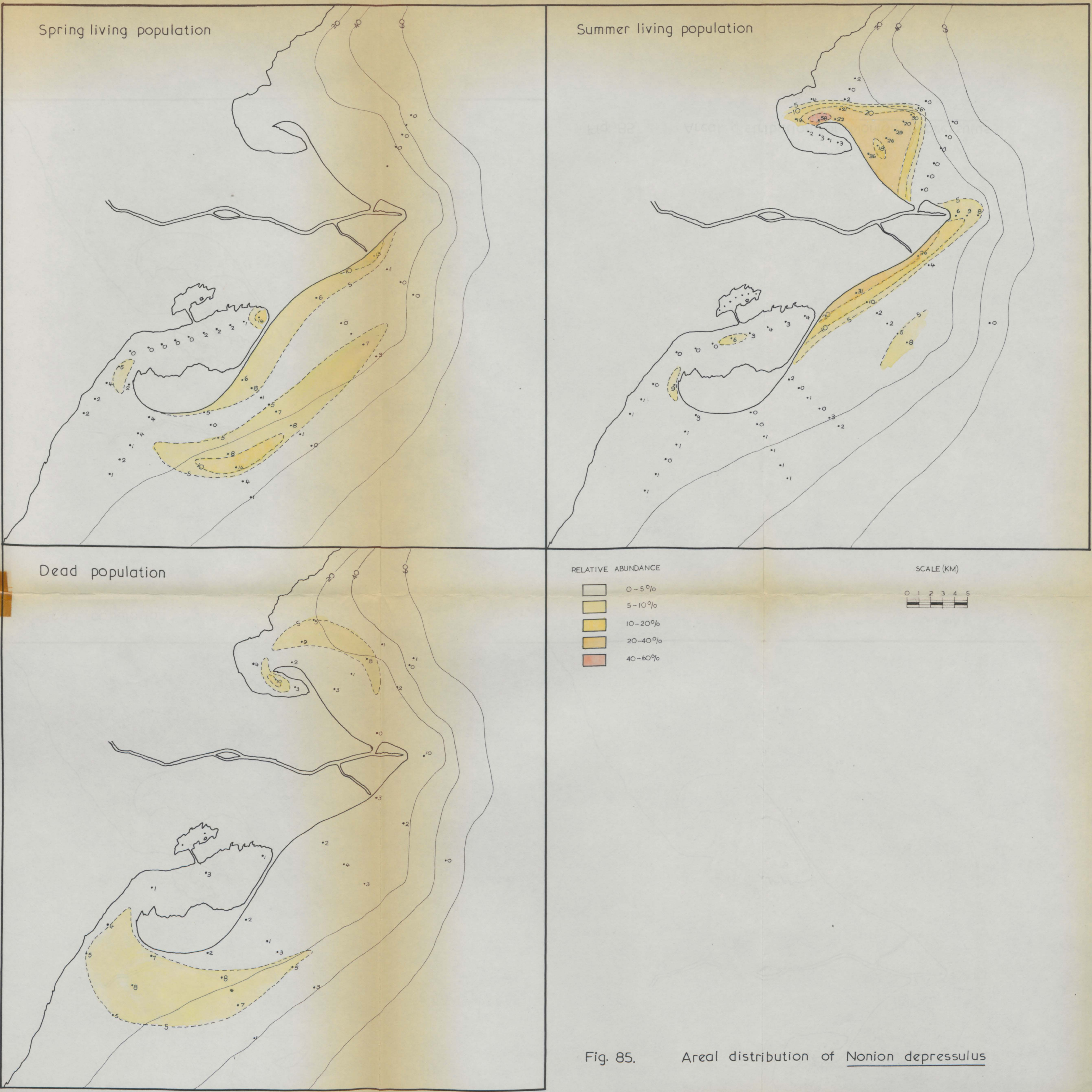
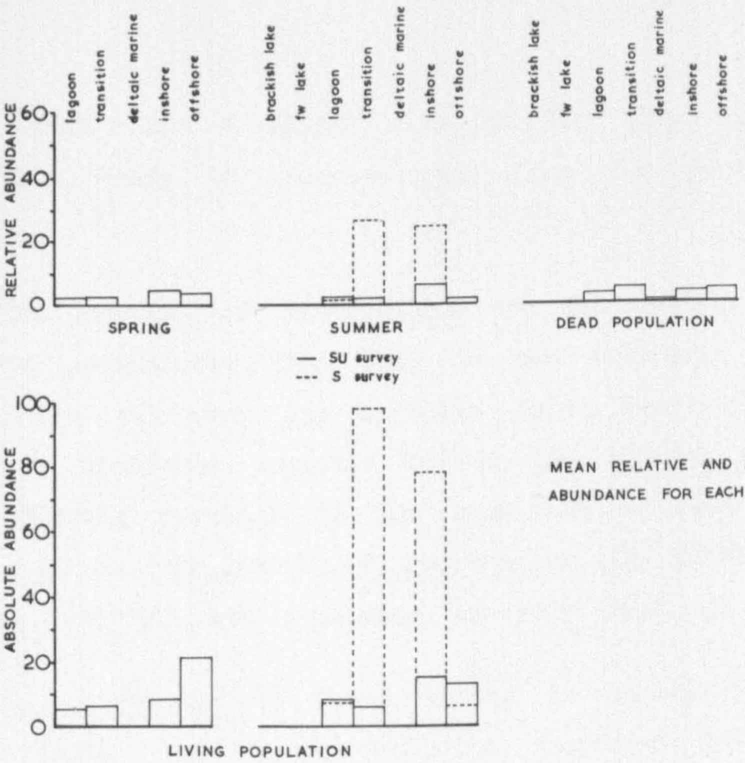
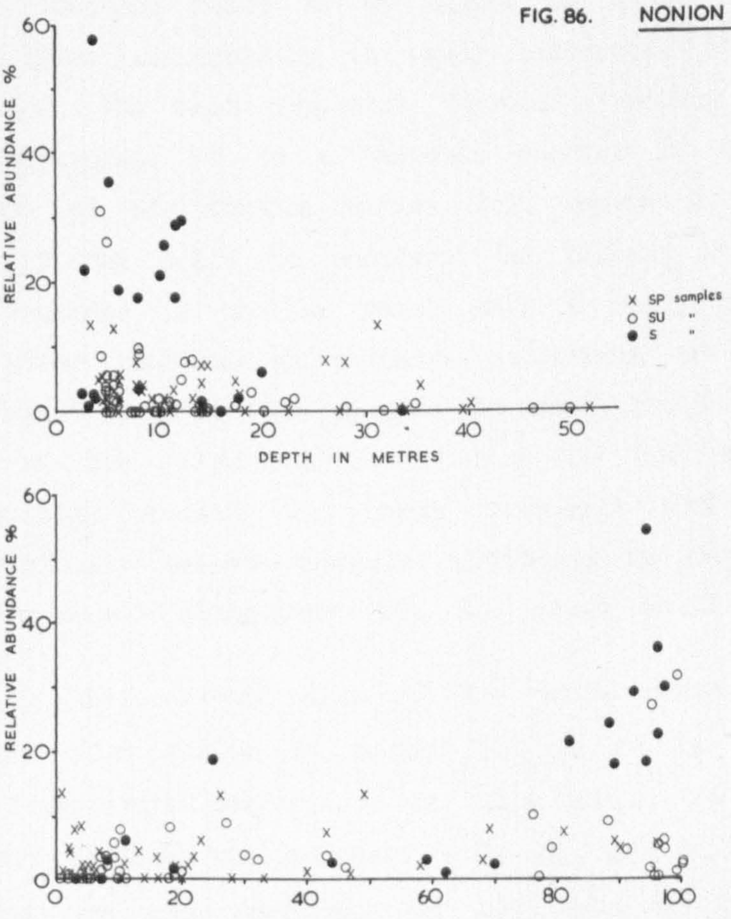


Fig. 85. Areal distribution of Nonion depressulus



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 86. **NONION DEPRESSULUS**



and, apart from a slight rise on the edge of the delta front platform, tends to decrease away from the shore with increasing depth.

The pattern of distribution on the northern side of the delta differs appreciably from that on the southern side. Percentages are very high all over the northern delta front platform and the relative abundance contours follow the outline of the platform rather than running parallel to the coastline as they do on the southern side. As in the spring, N. depressulus is absent from the river mouth traverse, but abundance is very high in the transition area.

N. depressulus is found living in waters from less than 2½ to 40 m. depth but highest relative abundance (more than 20%) only occurs within a more restricted range, from 3 - 12½ m. (see figure 86). Abundance tends to be higher in sandy sediments but the species also lives successfully in muddy sediments. It is difficult to ascertain the most important factors affecting the distribution of N. depressulus. It is a variable species in the sense that its pattern of distribution varies from season to season and from one side of the delta to another. The highest relative abundance values are recorded in shallow water with a sandy substrate, but there are other stations where these conditions are fulfilled but where abundance is low. The species is most abundant on the northern side of the delta and it is possible that it prefers the conditions of higher fertility and lower turbulence that probably exist there. It obviously cannot tolerate conditions of rapid sedimentation because it is absent altogether from the river mouth area.

On the southern side of the delta abundance is not noticeably changed from spring to summer and so it is not possible to suggest any temperature preferences on this basis. As the spring survey did not include the northern side of the delta it is not known whether the high abundance in that area is due to a phase of of reproduction or whether abundance is high all the year round.

The dead population shows a very interesting pattern of distribution (figure 85). Relative abundance is highest in two crescentic areas which curve around the two spits. The positions of these two highs do not coincide with any areas of high abundance in the living population and it is likely that post - mortem redistribution of empty tests of N. depressulus is quite considerable. Transport probably occurs parallel to the coast along the delta flanks from the areas of high production and some of the tests are deposited in the quieter water around the spits into the transition areas. Mean relative abundance values for the different assemblages are not significantly different from those for the living populations although the actual distribution within these assemblages is different as has already been described. The offshore and transition assemblages have slightly higher mean relative abundances than for either of the living populations probably due to transport of tests into these areas from the areas of high production in shallower water.

Recent and fossil occurrences:

There is great difficulty in determining the distribution of N. depressulus because of the widespread confusion over its nomenclature. Walker and Jacob described the type specimens from Reculver on the Kent coast and Murray (1965b) collected topotypes. He observed that the species is rare along this part of the British coast and added that in the type collections in the British Museum, forms normally referred to N. depressulus are in fact another species (Protelphidium anglicum Murray). Many specimens named Nonion asterizans should be referred to N. depressulus.

Specimens have been recorded as N. depressulus from samples as old as Upper Miocene but these occurrences cannot strictly be verified without reference to the toptype specimens. N. depressulus emend. Murray appears in modern samples from around the British Isles, the French Channel coast, Brittany and the northwestern Mediterranean.

Nonion laevigatum D'Orbigny

In the spring N. laevigatum is most abundant in a zone of less than 20 m. depth that extends from the southern delta front platform around the spit into the transition area (figure 87). It is widely distributed through all marine environments but, apart from the afore mentioned area, rarely reaches more than 1 or 2% of the living population. There is a remarkable change in the living population in the summer. Apart from a small area off the southern spit the species is totally absent from the southern side of the delta. On the northern side, however, it is much more widespread and there is a distinct high over the northern delta front platform. Unlike the spring, in summer N. laevigatum is more or less confined to the transition and inshore assemblages.

It is found living in depths from 3 - 53 m. but only becomes abundant in relatively shallow water of depth 5 - 15 m. (figure 88). The sediment / abundance plot indicates that higher percentages usually occur within sandy sediments although it also lives commonly in muddy sediments. N. laevigatum is unusual in that it has higher abundance on the southern side of the delta in spring than in summer whereas summer values for the northern side of the delta indicate even higher abundance. It is therefore impossible to suggest any temperature preferences for the species.

Empty tests of N. laevigatum are widely distributed throughout most assemblages but the relative abundance is somewhat less than

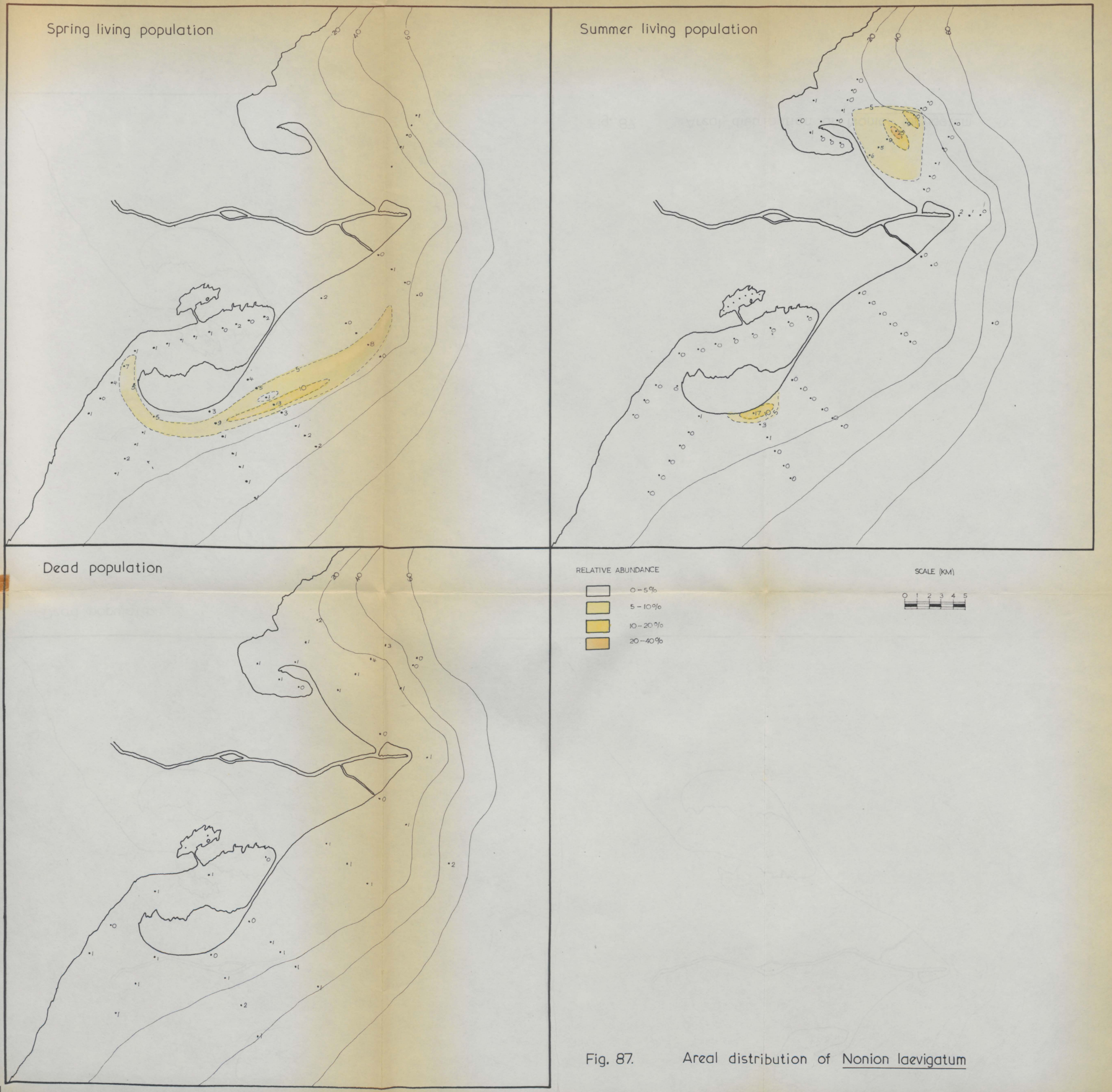
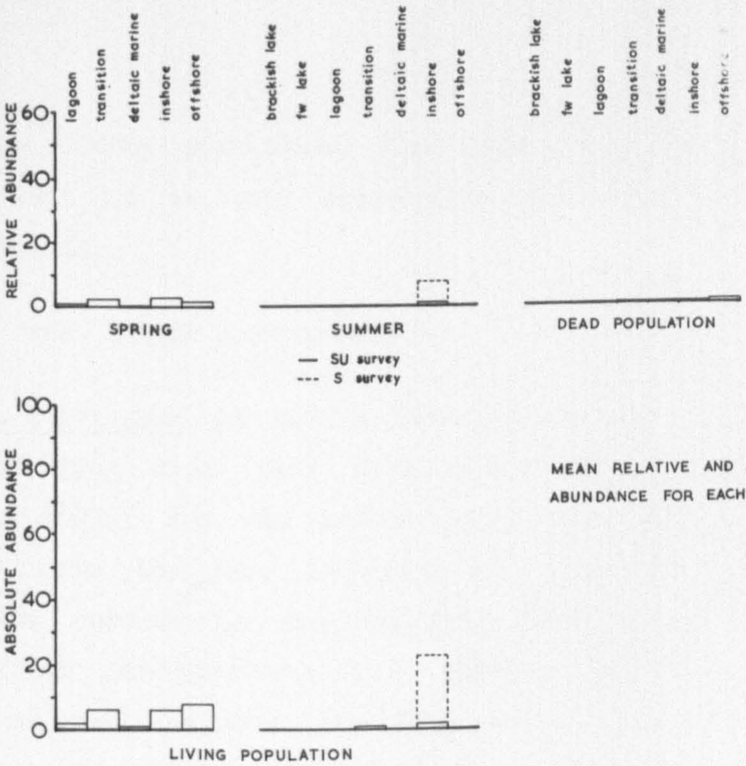
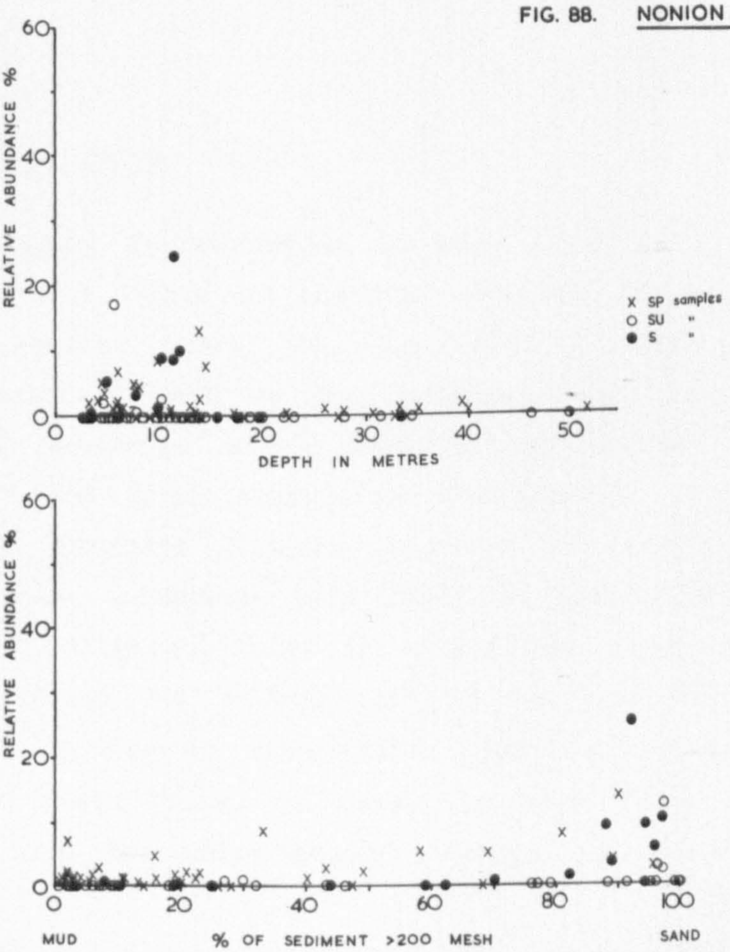


Fig. 87. Areal distribution of Nonion laevigatum



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 88. NONION LAEVIGATUM



for the living population. The small size of N. laevigatum probably means that it is very susceptible to post - mortem redistribution by currents.

Recent and fossil occurrences:

N. laevigatum is not a commonly recorded species. It was first recorded from beach sand from Rimini in the Adriatic but neither Cushman (1939) nor the author could find topotype specimens in samples from the same locality. It must be concluded, therefore, that the species is rare in that part of the Adriatic. However, the author has specimens from samples from Sicily and the Rhône delta as well as from the Ebro delta. The species has apparently not been recorded in any Tertiary deposits and its modern occurrences are limited to the western Mediterranean.

Nonionella opima Cushman

N. opima is widespread in most environments in the deltaic area and in terms of absolute abundance is one of the most common species around the Ebro delta. In the spring, apart from one record of 46 % on the southern channel traverse, highest relative abundance occurs south of the southern spit, reaching over 60 % at the final station in the Vinaroz traverse (figure 89). Relative abundance contours generally run parallel to the shoreline with values increasing with depth to approximately 35 m. when they fall off slightly. There is a distinct break in the contours over edge of the central part of the southern delta front platform and the species is absent from many stations nearshore along the southern delta flank. It occurs in high frequencies in the transition area but only extends a short way into the southern lagoon.

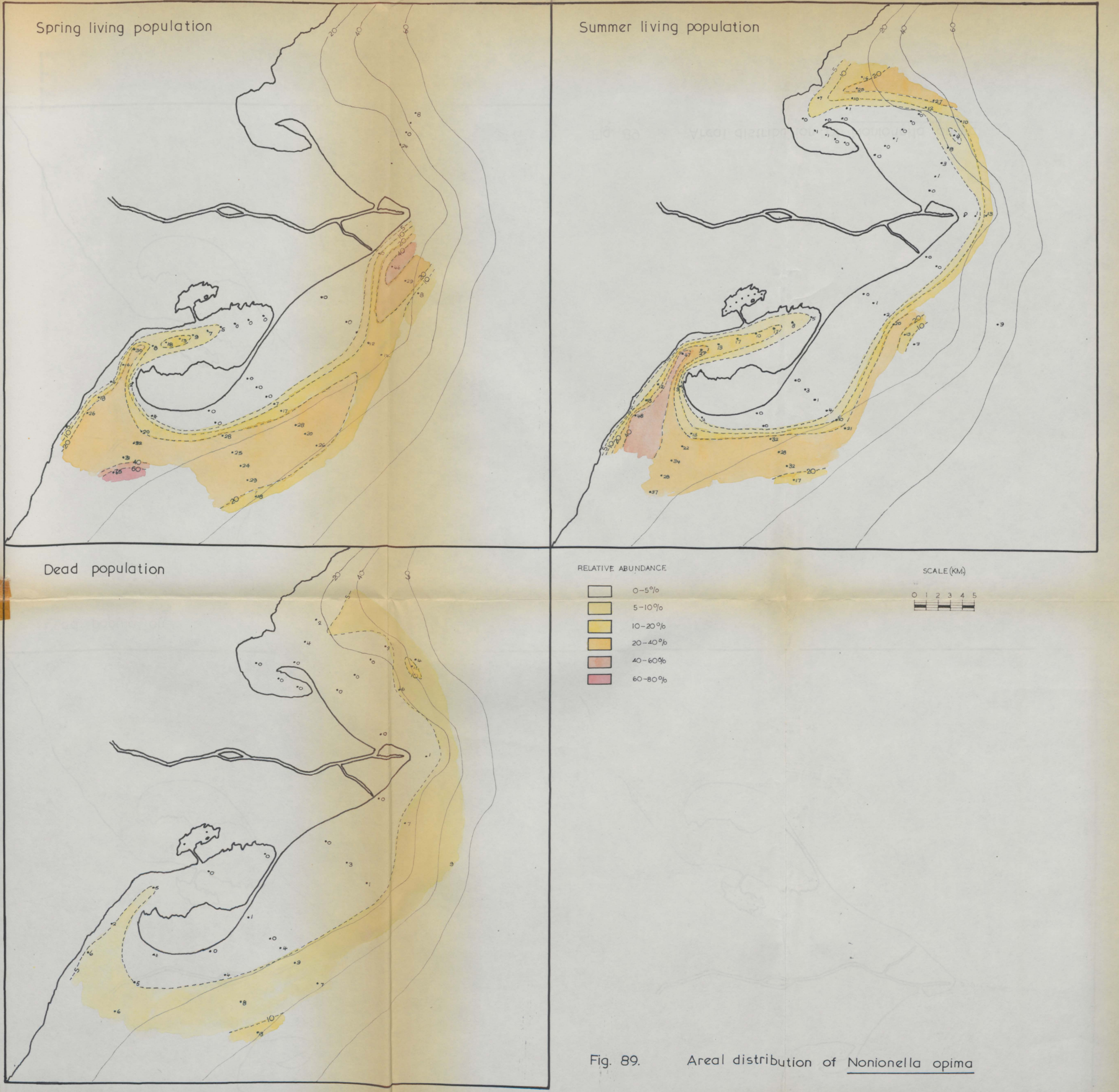
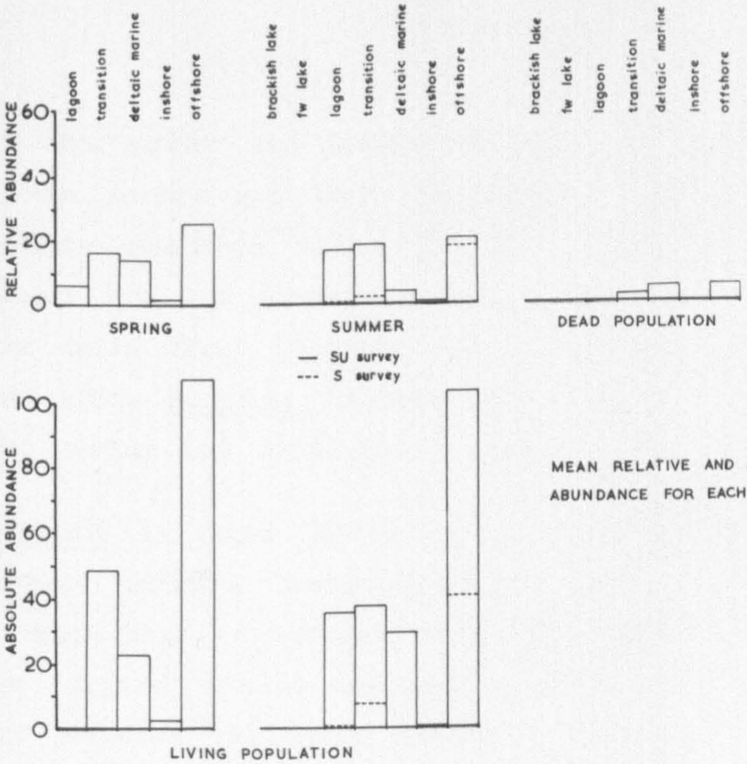
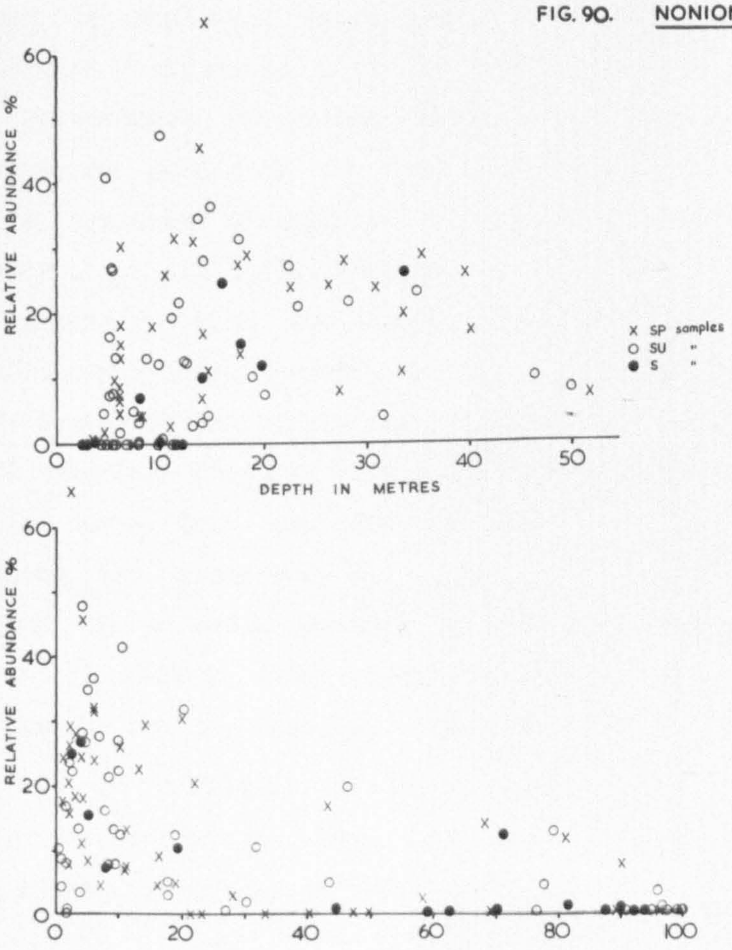


Fig. 89. Areal distribution of Nonionella opima



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 90. **NONIONELLA OPIMA**



In the summer the pattern of distribution is much the same as in the spring and there is little change in the mean relative or absolute abundance values for the different assemblages. Again, percentages are low throughout the inshore assemblage over the southern delta front platform and this trend is repeated on the northern side. N. opima is much more abundant in the southern lagoon than in spring but abundance is low in the northern lagoon.

N. opima is found living in depths from 3½ - at least 53 m. but highest relative abundance occurs within a range of 4½ - 39 m.; deeper than this percentages gradually fall off. It is basically an open marine species occurring only in normal salinity but it is very abundant relatively nearshore along the Las Casas traverse and to a lesser extent in the western part of the southern lagoon. This can be explained by a preference for muddier sediments. From the sediment / abundance plot in figure 90 it can be observed that higher percentages invariably occur in the muddier grades of sediment. The increased abundance in the southern lagoon in summer correlates with the presence of muddier sediments at that time, while the relatively low abundance towards the edges of the delta front platforms correlates with the sandy nature of the sediments there. Also the anomalously high record of 46 % at one station on the southern channel traverse in spring is coincident a much muddier substrate at that station compared with other stations on the traverse. It certainly seems that sediment is more important than depth in determining the occurrence of N. opima in nearshore stations, but there may be a depth control on the deepest limit of the species offshore. In deeper water stations percentages fall off despite the muddy nature of the sediment. As with other species showing similar trends, it is difficult to know whether N. opima actively prefers the physical conditions that occur in muddy sediments or whether it is simply not tolerant of the turbulent conditions associated with sandy sediments.

As far as can be determined from the spring and summer occurrences, temperature has little effect on the abundance of N. opima. There is little change in relative or absolute abundance from spring to summer and at each season the population has an average of 19 % of juvenile specimens (specimens less than 100 µ in length). This would suggest that reproduction is continuing at a constant rate at least through a temperature range of 13 - 26°C.

The most notable feature of the dead population is the low relative abundance compared to the living populations. At only two stations do values exceed 10 % relative abundance and although percentages increase with the depth as with the living populations, the falling off of values in deeper water is not apparent. All this suggests that post - mortem redistribution of empty tests of N. opima is very marked. The absence of the fall off of percentages in the deeper water stations might indicate that a number of tests are transported from shallow to deeper water.

Recent and fossil occurrences:

N. opima appears to be strictly a Recent species; no records have been found from the Upper Tertiary.

Cushman described the type specimens from off Cape Canaveral, Florida, and there are many records from the Gulf of Mexico. It is particularly common around the Mississippi delta and Lankford (1959) noted that it is particularly abundant in the deltaic marine environment. He also noted that it shows "considerable variation in size, shape and degree of chamber inflation" which is in agreement with Ebro delta specimens. In the sound environment (which roughly to the Ebro delta lagoonal environment) N. opima has lower frequencies and a mean length 20 % greater than specimens from the deltaic marine environment. His measurements were as follows: (Ebro delta measurements for comparison)

Mean length μ

	Mississippi		Ebro
Sound	223	Lagoon	236
	-	Transition	210
	-	Inshore	208
	-	Offshore	196
Deltaic marine	185	D. marine	154

The trends exhibited are the same for both localities; larger specimens tend to be found in the lagoon or sound environment and smaller specimens tend to occur off the river mouths. Lankford concluded that a species has the smallest average size where environmental conditions are optimum and the largest size where conditions are most vigorous. Although the author agrees in principle with Lankford's conclusions, reservations must be expressed concerning the use of size data. Fully adult specimens will reveal trends of size variation but trends will usually be concealed by juvenile specimens in various stages of development.

Parker et al. (1953) recorded the species from San Antonio Bay in southwest Texas and Todd and Brönniman (1957) found it abundant in the offshore zone (4 - 34 m. depth) in the Gulf of Paria which is under the influence of the Orinoco delta. N. opima also occurs commonly in the western Mediterranean. Todd (1958) recorded the species from deep sea cores in the western Mediterranean and correlated the occurrence with a West Indian fauna. Blanc - Vernet (1963) recorded various species of Nonionella as very abundant living forms in the Gulf of Marseille and says that they are characteristic of muddy sediments. The author also has specimens from off the Rhône delta and it appears to be quite common in most environments there although Kruit (1955) did not record it.

It is possible to conclude from the above occurrences that N. opima is typically a deltaic species, flourishing best under deltaic marine conditions with a muddy substrate, but more investigations are necessary before this can be confirmed.

Total Textulariina

Many stations in both spring and summer have many species of Textulariina although few of them are particularly abundant individually. Many are quite widespread and so it was considered worthwhile examining the distribution of the Textulariina as a whole.

In the spring abundance is very low in the southern lagoon and the inshore assemblage. Percentages are consistently higher in the offshore assemblage and there is a trend for increase with depth. High abundance is also recorded off the river mouth (see figure 91).

In the summer relative abundance is slightly lower than for the spring. There are again few records in the lagoons but off the delta flanks percentages increase with depth up to about 15 m. on the southern side and about 20 m. on the northern side. Deeper than this they level off or even decrease slightly. The high percentage nearshore on the Cabo Tortosa traverse is due to a local abundance of Reophax scottii but in most other stations the total percentage of Textulariina is made up by smaller proportions of several species.

The abundance / depth plot (in figure 92) illustrates that

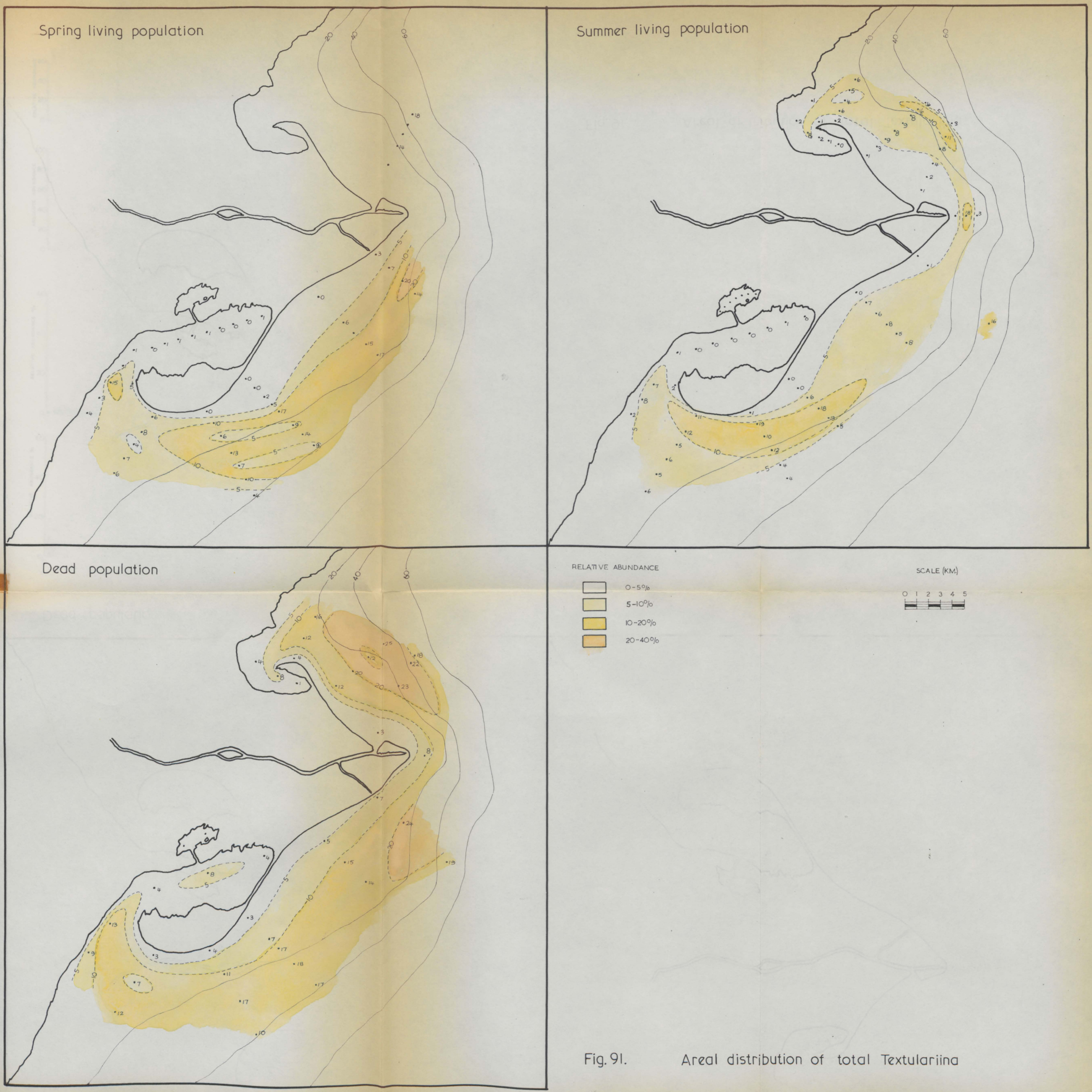


Fig. 91. Areal distribution of total Textulariina

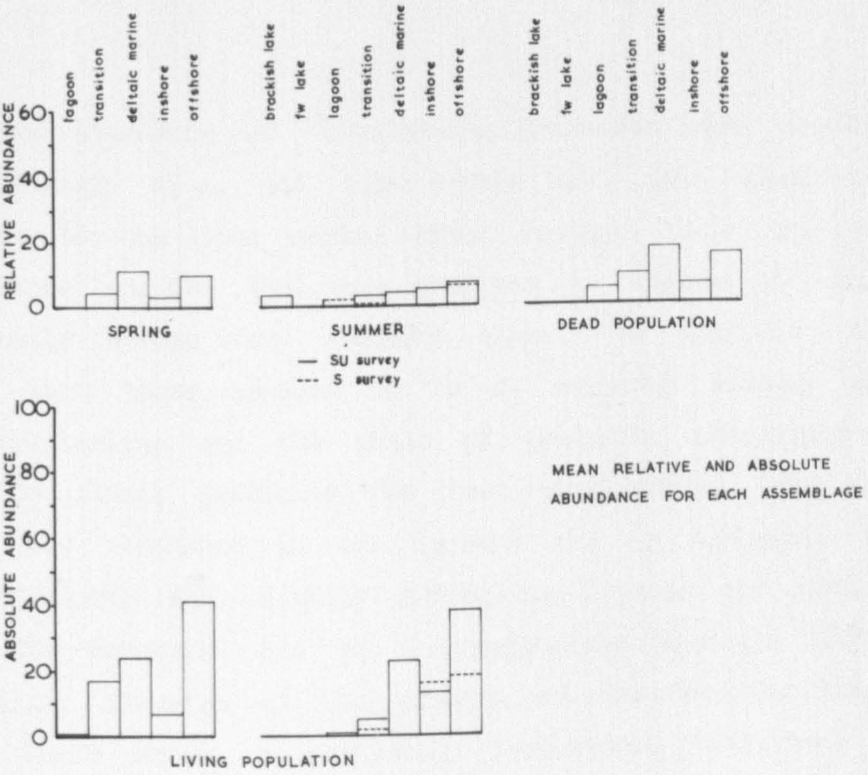
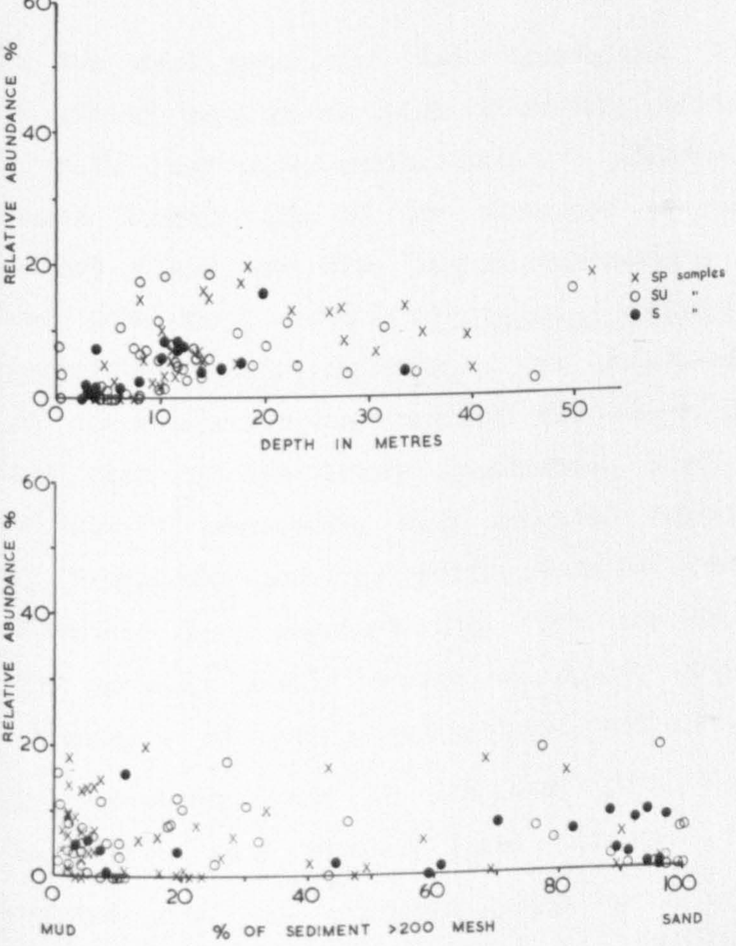


FIG. 92 TOTAL TEXTULARIINA



there is an organic agent holding the test together whilst the species is living, but when it dies this cement or lining decays and the sand particles of the test fall apart. Reophax scottii also has a very delicate test and is relatively rare in the dead population.

Total Miliolina

It was observed during population counts that many stations had very large numbers of dead miliolids and others had large numbers of small living miliolids that were frequently unidentifiable because of their small size and because many species are very alike in their early stages. Many of these unidentified forms have similar environmental preferences and for these reasons the distribution of the Miliolina as a whole was examined.

In the spring highest relative abundance of miliolids occurs a short distance from shore over the southern delta front platform. The inshore assemblage as a whole has the highest mean percentage of miliolids, largely due to the abundance of Q. schlumbergeri, but absolute abundance is higher in the transition area. The offshore assemblage has a relatively low mean percentage and it can be observed from the areal distribution map (figure 93) that miliolids become less abundant in deeper water. Values in the southern lagoon are generally low, but there is a high in the northeastern corner where Triloculina rotunda and others are abundant.

In the summer miliolids are still very abundant over the southern delta front platform although the area of highest relative abundance has shifted farther south and the relative abundance contours approach closer to the shoreline. Values are again relatively low in the southern lagoon but the high in the northeastern corner

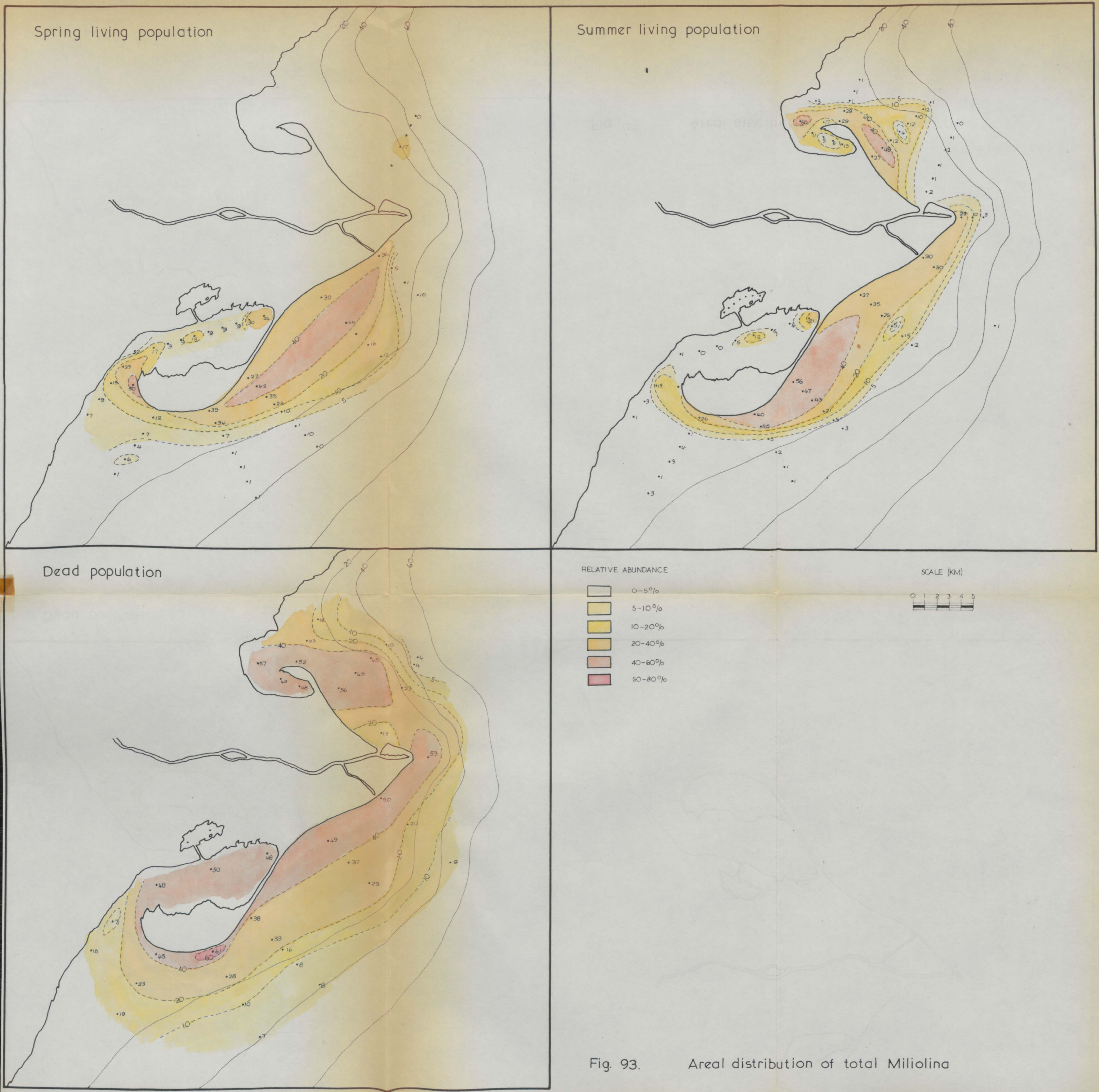
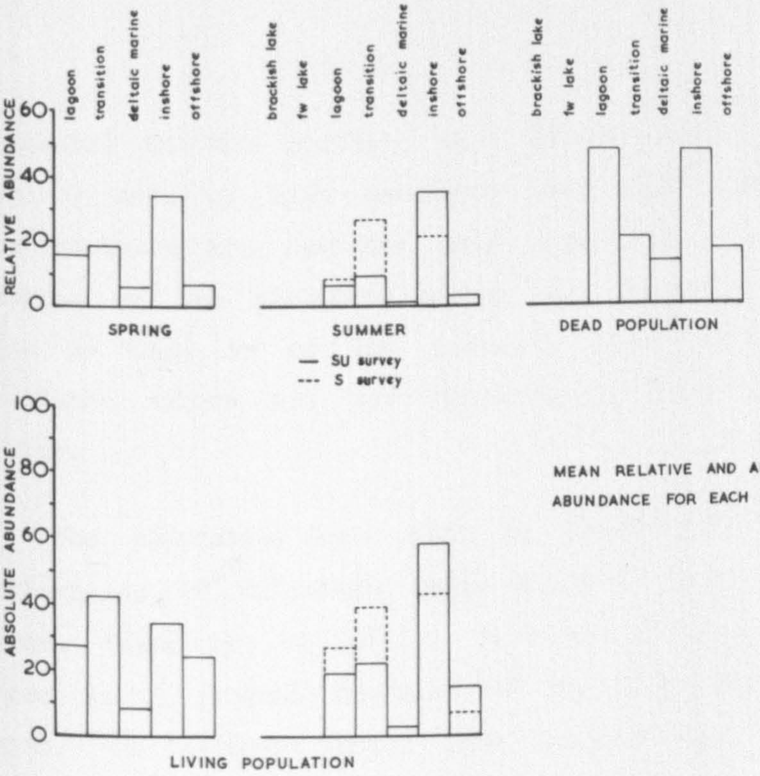
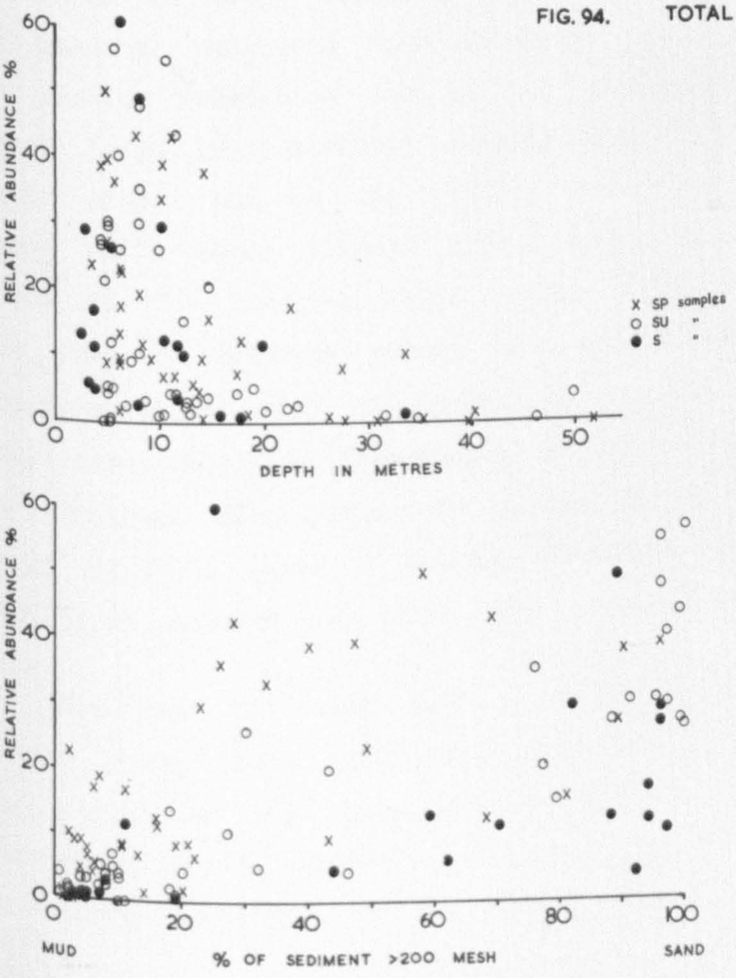


Fig. 93. Areal distribution of total Miliolina



MEAN RELATIVE AND ABSOLUTE ABUNDANCE FOR EACH ASSEMBLAGE

FIG. 94. TOTAL MILIOLINA



persists. On the northern side of the delta there is a corresponding area of high abundance over the delta front platform but the contours are deviated away from the coastline to follow the outline of the platform rather than running parallel to the coastline as they do on the southern side. Mean relative and absolute abundance values are not significantly different from those of the spring.

The abundance/depth plot in figure 94 shows that the highest percentages of miliolids occur close to the shoreline in shallow water. There is an optimum of about 6 m. depth and following this there is a gradual decrease of relative abundance with increasing depth. The sediment/depth plot demonstrates that miliolids are not usually very abundant in muddy grades of sediment but reach greater abundance in sandy sediments and in sand/mud mixtures. From this it must be concluded that miliolids are more successful as a group on sandier substrates and do not favour the muddy substrates that exist (even in relatively shallow water) in the lagoons and transition areas, and on the Vinaroz and river mouth traverses. The group as a whole favours normal salinity and no species were found in the brackish water areas. Some species in other regions are able to tolerate waters of less than normal salinity but Murray's (1968) plot of hyposaline lagoons shows that the latter only have very low frequencies of miliolids. There is little change in abundance from spring to summer so it appears that the whole group does not have a general temperature preference, but obviously individual species may show some seasonal variation.

The dead miliolids have a similar distribution pattern to the living ones; there are 'highs' over the delta front platform on both sides of the delta and percentages generally fall off with increasing depth. However, relative abundance is higher in all assemblages compared to the living populations and one of the obvious features of all foraminiferal floats is their high miliolid content. Many of these tend to be the larger species, particularly Quinqueloculina longirostra, Q. seminulum and Triloculina dubia, and it may be that because of their large size they are less readily redistributed by currents. The relative abundance of miliolids would therefore build up in the dead population as smaller species from other groups are winnowed away.

Another reason for the dead population being proportionally greater that the living is that there are several species in the dead population that do not occur in the living, particularly in the lagoons, for example, Vertebralina striata. Because of the widespread confusion in miliolid taxonomy, it was not considered worthwhile identifying most of these species. Their origins are unknown but there are a few possible explanations for their presence:

1. They were derived from other areas; nearby environments or even farther afield where they are living at present.
2. They are reworked from older deltaic deposits, having lived in the deltaic area some time ago.
3. They are species that until relatively recently were living in or near the environments in which they are found and have since died out but are still represented in the dead population.

The author considers that 1 and 2 are the most likely explanations. In the case of the lagoons several species of Miliolina that are rare in the sediments have been observed living on the large areas of weed that cover the sea floor. When these die their tests are contributed to the surrounding sediment and so the proportion of miliolids in the sediment is not a true reflection of those actually living in the sediment itself.

Other species

Apart from the species already desribed in detail, there are many others that were observed to have definite ecological requirements and it is proposed to mention some of these briefly. A great number of the living species from the Ebro delta, however, are relatively rare and have only irregular occurrences in low frequencies and little can be determined about their ecology.

Cyclogyra incerta occurs in most assemblages where the substrate is muddy. Occurrences are limited to a few individuals offshore but it is most abundant in the southern lagoon, particularly in the spring when it attains 16 % of the living population at station SP/43. This particular sample was largely of weed, and although the species was not observed attached to or living on the weed, it may well follow this mode of life. Transport of the weed to the surface and subsequent washings may have resulted in the tests being displaced from the weed. *Patellina corrugata* and *Triloculina rotunda* are abundant at the same station and were actually observed clinging to the weed. Both, however, were also found at other stations in the lagoons living on or within the sediment. *Rosalina concinna* and *R.* c.f. *R. mediterranensis* were similarly found on weed but again both were also found in sediments of the lagoons and transition areas. *Bolivina pseudoplicata* and *Brizalina striatula* are also confined largely to the lagoons and the latter is slightly more abundant in spring. *Buliminella elegantissima* and '*Rotalia*' *perlucida* occur frequently at relatively shallow water stations with a muddy substrate but reach their greatest abundance in the lagoons. *Rosalina* c.f. *R. valvulata* occurs sparsely in the lagoons but is most abundant in summer at the northern end of the Las Casas traverse; it appears to favour the quiet, shallow water conditions of the transition areas.

Fursenkoina schreibersiana is fairly common in the lagoons and the southern transition area, especially in summer, while *F. complanata* occurs in low frequencies in many offshore samples, usually in muddy sediments. *Elphidium advenum* is widespread through most assemblages from the lagoons to the deepest offshore stations and must be a very tolerant species since it occurs through a wide depth range, a wide range of sediment types and in varying conditions of turbulence. However, it never reaches great abundance; the highest percentages occur towards the ends of the Vinaroz and Faro traverses suggesting that the species may be more abundant away from the deltaic influence. *E. crispum* is common off the delta flanks in low frequencies but is never found close to the shore or in the deepest water sampled. It is most abundant along the Vinaroz traverse in spring. *E. oceanense* is a brackish water species; only one or two specimens were discovered in the normal salinity water of the lagoons. It appears to be most successful in the brackish waters that occur around the edges of the lagoons and in the shallow brackish lakes on the subaerial part of the delta. Its absence from Encanizada suggests that it cannot tolerate water of extremely low salinity; the minimum salinity in which it was found living is 9°/oo. Murray (1961) discovered similar affinities when studying its ecology in Christchurch Harbour.

Gavelinopsis praegeri is found almost exclusively in muddy sediments in a range of depths from the shallow water of the transition area to some of the deepest stations off the delta flanks. It is notably more abundant in summer suggesting a preference for warmer temperatures. *Asterigerinata mamilla* is found in almost exactly the same environments but it is more abundant in spring. This would tie in with it being generally recognized as a cool water species; it is particularly common around the British Isles.

Uvigerina sp., *Cassidulina laevigata* and *Florilus scaphus* all have similar affinities, preferring deep water. Their occasional

Table 10: Summary of ecological data on the most abundant species.

	Optimum environmental conditions observed around the Ebro delta					
Species	Assemblage	Season of max. abundance	Salinity	Substrate	Depth	Other observations
Eggerella scabra	All marine assemblages	no preference; ?eurythermal	Normal marine	All grades	2½ – 53m.	Relative abundance much greater in dead population.
Quinqueloculina schlumbergeri	Inshore, transition	no difference; ? eury thermal.	Normal marine	Sandy	4 – 11m.	Most abundant in areas of near-shore turbulence.
Triloculina sp.	Inshore	Summer	Normal marine	Sandy	<14m.	
Brizalina pseudopunctata	Transition, offshore, delt.marine	Summer	Normal marine	Muddy	5 – 33m.	
Bulimina aculeata	Deltaic marine	Summer	Normal marine	Muddy	>19m.	Very successful under conditions of rapid sedimentation.
Hopkinsina pacifica/atlantica	Lagoon, transition	no difference; ?eurythermal	Normal marine	Muddy	5 – 9m.	Appears to favour a situation close to the entrance to a lagoon.
Rectuvigerina c.f. R. compressa	Offshore	no difference; ?eurythermal	Normal marine	Muddy	27m.	
Eponides granulata	Inshore	Summer	Normal marine	Sandy	8 – 15m.	
Epistominella vitrea	Deltaic marine	Summer	Normal marine	Muddy	>25m.	Flourishes in areas of active sedimentation; may be typically a deltaic species
Valvulineria complanata	Deltaic marine	Spring	Normal marine	Muddy	>25m.	Never found closer than 1km from shore intolerant of near-shore turbulence.
Asterigerinata sp.	Inshore	Spring	Normal marine	All grades except 'purest' muds	3 – 11m.	Flourishes in nearshore turbulent zone.
Ammonia beccarii	Lagoon, lacustrine	Summer	Normal marine/ brackish	All grades	<10m.	Very successful species, tolerant of a wide range of environmental conditions
Elphidium c.f. E. flexuosum	Transition	Spring	Normal marine	Muddy	9 – 13m.	Possibly more abundant off non-deltaic coastline.
E. lidoense	Offshore	Summer	Normal marine	Muddy	6 – 15m.	Although most abundant in offshore assemb., it is not distributed evenly.
E. selseyensis	Offshore	Summer	Normal marine	Muddy	6 – 17m.	Similar affinites to, and strong association with. E. lidoense
E. sp. 1	Offshore	No difference; ?eurythermal	Normal marine	Muddy	12m.	
Protelphidium anglicum	Freshwater lacustrine	No difference; ?eurythermal.	Brackish-freshwater	Muddy sands.	< 2m.	
Nonion depressulus	Inshore	No difference; ? eurythermal	Normal marine	Sandy	3 – 12½m.	
N. laevigatum	Inshore	?	Normal marine	Sandy?	5 – 15m.	Most abundant in spring offshore; in summer more abundant inshore.
Nonionella opima	Offshore	No difference; ?eurythermal	Normal marine	Muddy	4½ – 39m.	?Typically a deltaic species.

occurrences in relatively shallow water in the transition areas is attributable to a liking for muddy substrates. Brizalina spathulata occurs commonly in deep water at stations with a muddy substrate. Melonis pompilioides and Bulimina sp. 1 are found only at a few stations in the deepest water sampled and are obviously species whose minimum depth range (probably about 50 m.) just comes within the range sampled off the delta.

Nonion asterizans is a fairly shallow water species although it does not occur at the stations with very turbulent conditions very close to the shoreline. It shows greatest abundance in sandy sediments but also lives in sediments of sand / mud mixtures. It has a preference for warmer temperatures since it is more abundant in summer. Nonion c.f. N. germanicum has a similar ecology being most abundant in summer in nearshore stations on the delta front platform. Elphidium incertum also has similar environmental preferences- shallow water (down to 12 m. depth) and a sandy substrate, but it is confined almost exclusively to the northern side of the delta.

Bulimina gibba is a common species at both seasons in the offshore, deltaic marine and transition environments. It has a wide depth range but is rarely found in sandy sediments. The species of Nodosariacea are widely distributed but have no regular pattern of distribution. There are usually only one or two individuals at the stations where they occur. They are invariably found on muddy substrates and the delicate nature of their tests probably means that the turbulent conditions associated with sandy sediments would probably cause them damage.

d) DEAD POPULATION

The dead populations from most stations were counted for comparison with the living populations. However, empty tests were so abundant in the floats that it was impractical to use the same counting method as was used for the living populations. As has already been explained in chapter 6, 250 - 300 dead individuals were counted and identified from a portion of the float and the percentage abundance of each species calculated. As this data is qualitative, only broad comparisons with the living populations, based on relative abundance, are possible. Post - mortem distributions of the more important species are discussed in the section on specific ecology and it is proposed to limit this section to more general aspects of the dead population and its relation to the living population. Dead population data is recorded in Appendix 2c.

Size of the dead population

Quantitative data on the numerical abundance of dead tests is not available, but in all floats it was observed that empty tests considerably outnumber the 'living' (i.e. stained) individuals. However, the significance of this observation is doubtful because it is likely that the proportion of empty tests in relation to living ones increases with depth in the sediment. With a sediment sample of 1.5 cm. depth, the surface may be dominated by living individuals but the lower layers may have predominantly dead tests. Therefore, as each sample is processed as a whole, no significance can be attached to the ratio of living/empty tests in the floats. It is perhaps more appropriate to discuss the factors that might influence the size of the dead population; these can be listed as follows:

1. Death rate in the living populations, i.e. the rate at which

tests are contributed to the sediment.

2. The effects of post - mortem redistribution and destruction of tests.

3. The rate of sedimentation.

The rate at which tests are contributed to the sediments depends not only upon the life span of the species but also upon a number of other factors. Murray (1967) defined the annual production of foraminiferids as the "Number of tests contributed to a unit area of sea floor during the course of one year", and he added that the production will depend on four main factors: the initial size of the standing crop, the proportion of individuals which reproduce, the frequency of reproduction, and the number of new individuals resulting from each reproductive phase. All these factors are in turn affected by environmental conditions. Temperature, salinity, food availability and other factors undoubtedly influence production, and seasonal variations in these factors will cause variations in the reproductive activity, and it is probable that there will be corresponding seasonal variations in the numbers of tests added to the sediment. Only two studies have so far considered production rates in foraminiferids. Myers (1942) considered that "Not less than 1000 tests of Elphidium crispum per sq. ft. are contributed annually at the stations worked", while Walton (1955) in a study of Todos Santos Bay, Baja California, estimated that 100,000 tests per sq. m. were added to the sediment each year at a depth of 37 - 92 m., while 650,000 were added at 545 - 735 m.

Although tests may be contributed to the sediment at a particular spot, they do not necessarily remain there. As the foraminiferids become part of the sediment they are subject to the same sorting processes as the sediment as a whole. Bottom currents may be active over the sediment and smaller tests would be especially susceptible to redistribution. Currents may be selective in other ways, in that tests of a certain size or shape may be concentrated in particular areas. Current activity off the Ebro delta is quite strong, and in has been demonstrated in the section on species ecology that the empty tests of many species are transported parallel to the delta flanks away from the centres of high standing crop. There is also evidence for transport of smaller numbers of tests from shallow to deeper water. Storms may also radically alter the dead populations; prolonged storms may disturb the sediment and Murray (1965) reported the presence of empty tests of benthic species in plankton samples from the English Channel taken after such a long period of storms.

Another factor that affects the size of the dead population is the rate of destruction of tests. This is very much an unknown quantity but the presence of many broken tests in most floats emphasises that it does go on. Abrasion and fracturing of tests probably occurs during active transport by currents. Again, the process is probably selective in that certain species having more delicate tests will be more prone to damage or destruction.

The rate of sedimentation is very important in determining the size of the dead population per unit volume of sediment. For example, a sample with a large dead population per unit volume of sediment could be interpreted as either representing very low production in an area of slow sedimentation, or alternatively, very high production in an area of moderate sedimentation. The dead population is largest over the Ebro area in the lagoons; station SP/42 yielded 13 ml. of foraminiferids, 3.2 % of the total sediment. The size of the living population in the lagoons, in relation to those in other environments, is moderate suggesting that production is also moderate while sedimentation is relatively slow. Most rapid sedimentation occurs off the river mouth where stations have very small dead populations per unit area of sediment. Large dead populations occur in Encanizada where sedimentation is also slow, while in the open marine environments they are relatively small reflecting the faster rate of sedimentation.

Composition of the dead population

α indices have not been used to measure the diversity of the dead populations because the data is not quantitative. Most dead population counts revealed a larger number of species than were encountered in the equivalent living populations. This suggests a higher diversity in the dead population, but again depth of penetration of the sample into the sediment may affect the results so that comparisons are invalid. However, the number of species per 250 individual count follows the same trends as the diversity of the living population with highest values offshore and lower values inshore and in the lagoons.

In most cases, species that are present in the dead population and absent in the living population, or vice versa, are those those that occur commonly through the deltaic area but which have not been encountered at that particular station. No significance is attached to the absence of a species in one population when it only occurs in the other in very low frequencies. The presence or absence of such species may be largely governed by counting methods, e.g. the separated portion of the float for a count of 250 dead individuals may not contain a particular species, but it may still be present in the sample in the portion not examined. For this reason only differences between the more abundant species in the living and dead populations are considered significant.

One of the most notable features of the dead population that distinguishes it from the living at many stations is the presence of planktonic species. These are confined to the open marine environments; none are encountered in the lagoon or 'subaerial' environments. They occur often as shallow as 7 m. and their relative abundance increases offshore, reaching up to 10% in some of the deeper stations (50 m.). The vast majority of planktonic individuals are *Globigerina bulloides* with smaller numbers of *G. inflata*, *G. pachyderma* and *G. quinqueloba*, all of which have been recorded as common in the Mediterranean, e.g. Todd (1958).

Another feature of the dead population is the relatively high proportion of Miliolina. Several species are present that were not recognized in the living populations, especially in the lagoons, but no attempt has been made to identify all these. In the case of the lagoons many of the species may live in areas not sampled, particularly on the large areas of weed, and the presence of *Vertebralina striata* and the abundance of *Triloculina rotunda* in the dead population of many lagoon stations may be because of transport over short distances from the areas where they are living. Three species of Discorbacea (not identified) are commonly found in the dead population of some lagoon stations and these may have the same origin. Increased abundance of miliolids is also characteristic of other environments and the triangular plot (figure 95) shows that the field of each assemblage is slightly different from its position for the living populations. Although the inshore and offshore fields are still distinct, the increased proportion of Miliolina has resulted in the lagoon field overlapping with the inshore field for much of its extent.

A few species, including *Cibicides lobatulus*, *Amphicoryna scalaris*, and *Gyroidina* c.f. *G. umbonata*, are found only in the dead population but they are not sufficiently abundant for their presence to be considered significant. Other species, such as *Eggerella scabra*, are markedly more abundant in the dead population compared to the living. The cause of this is obscure but it is possible that the tests

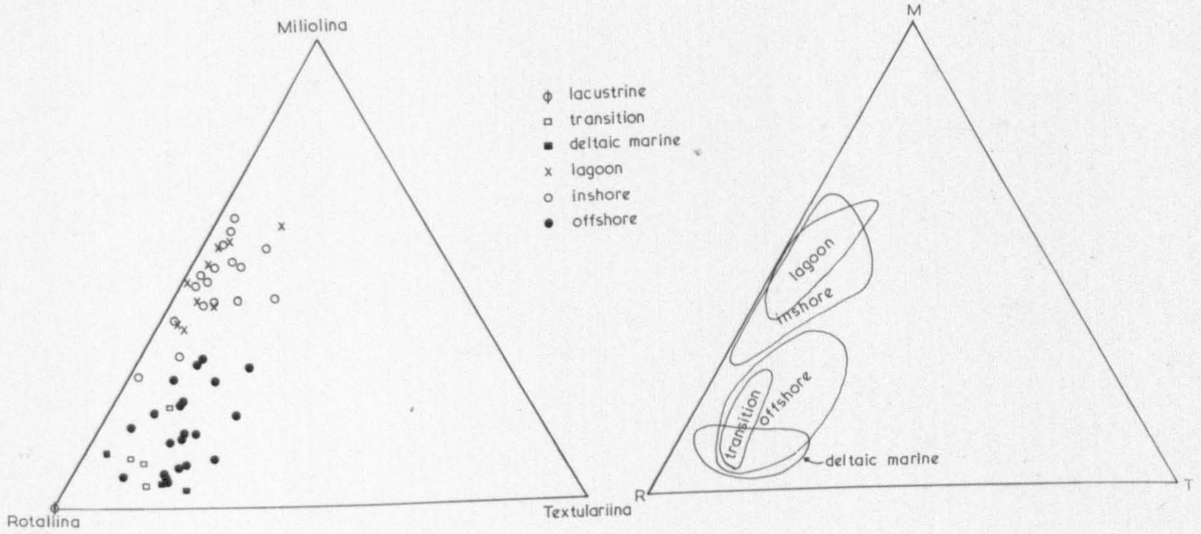


Fig. 95. Triangular plot of dead population analyses to show assemblage fields

may be too large to be transported away so that these species build up in relative abundance as the tests of other species are swept away. Alternatively, it is possible that an environmental change may have resulted in a population change so that the dead population is a reflection of the living population as it used to be.

A better example of the latter phenomenom is provided in Encanizada. The fauna is composed almost entirely of Protelphidium anglicum and Ammonia beccarii. Living specimens of the former tend to be most abundant in waters of very low salinity, while the latter prefers more saline water and is most abundant in waters of near normal salinity. The living population of P. anglicum at two stations in the lake is 100% and 99%, while in the dead population it comprises 57 and 30% respectively. The remainder of the dead population is made up of specimens of A. beccarii. The present salinity of Encanizada is very low, practically freshwater, and is more suited to P. anglicum, but the abundance of A. beccarii in the dead population suggests that relatively recently the water may have been more saline, perhaps like the brackish lakes in other parts of the delta where A. beccarii is dominant. It is possible that Encanizada only became dominantly freshwater when the delta first became irrigated and man - made drainage channels conducting freshwater from the river to the fields drained into the lake. It is unlikely that the dead specimens of A. beccarii were reworked because currents are non - existent in the lake, and it is equally unlikely that they were introduced from the lagoon since they are of the brackish water variety (var. 1, with the deeply excavated umbilicus) whereas indigenous lagoonal specimens are invariably var. batavus or var. 2 (the very small variety).

The most typical difference between living and dead populations is that species common to both have a lower relative abundance in the dead population. This is largely due to redistribution of of tests by bottom currents. Destruction of tests may also affect the composition of the dead population since certain species will tend to be damaged or destroyed more easily than others. For example, Saccammina comprima, which has a very loosely cemented arenaceous test, was never found in the dead population.

Certain areas ~~around~~ around the delta have relatively high proportions of non - indigenous individuals in the dead population. The 'transition' areas particularly have relatively high percentages of species that are most abundant in the living populations off the delta flanks. This is the result of current redistribution of tests; active transport along the coastline is followed by deposition in quieter water off the ends of the spits and in the 'transition' areas. There are few truly 'exotic' species in any of the dead populations, i.e. those that have been transported into the deltaic area from some distance away. A single peneroplid was recorded at station S/16 which had obviously been transported some distance because of the worn appearance of the test. The nearest record of peneroplids is in the Balearic Islands.

Normal mortality of foraminiferids follows the pattern of seasonal abundance of the living population; i.e. because individual species have preferred seasonal abundances there will be different species and different numbers of individuals contributed to the sediment at different times of year. Figure 96 shows the percentage similarity indices between living and dead populations at particular stations; it illustrates that at both seasons there is a considerable difference between living and dead populations with % SI's varying from 30 - 60%. Although addition of empty tests to the sediment varies from season to season, currents and other post - mortem redistributive agencies soon act on the newly deposited tests and redistribute them so that the dead population at any one position remains fairly constant throughout the year. Comparison of the

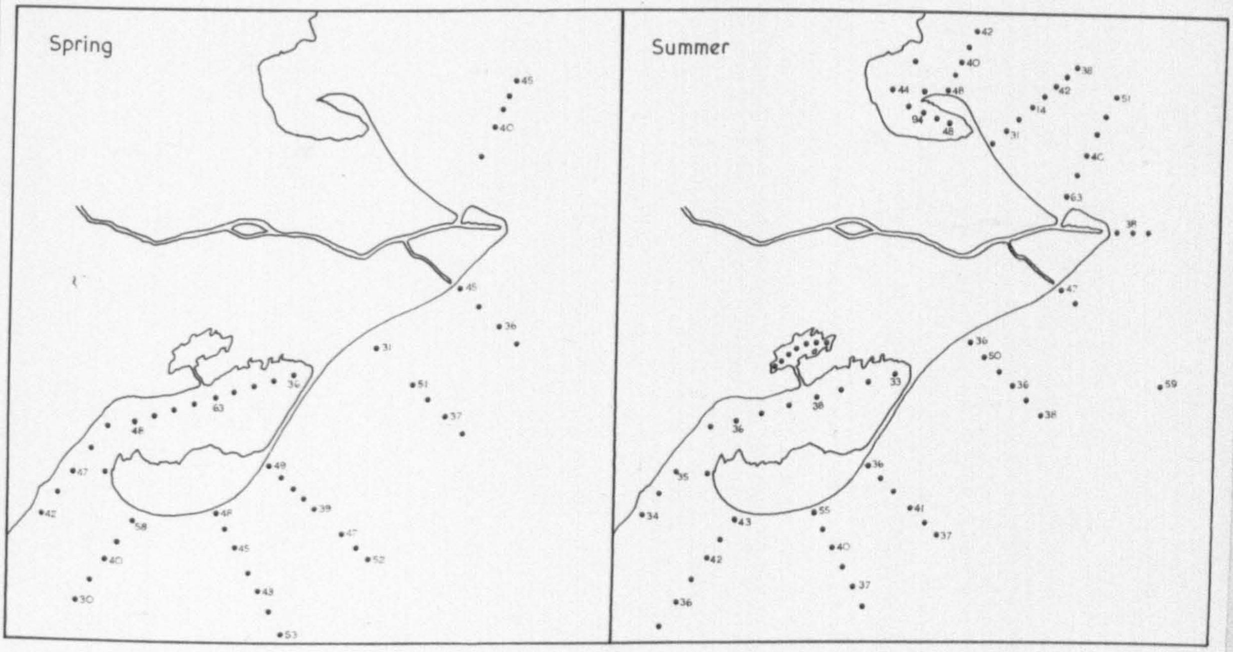


Fig. 96. Percentage similarity indices between living and dead populations at particular stations.

dead populations from corresponding stations for spring and summer surveys revealed SI's between 58 and 80%, with a mean of 68%. Allowing for errors in positioning of the corresponding stations, these values are high and confirm that there is very little change in the dead population from spring to summer, and probably throughout the year.

In summary it can be said that the dead populations around the Ebro delta differ from the living populations because of one or more of the following factors:

1. Seasonal mortality resulting in variation of the numbers of individuals and the species contributed to the sediment. However, these differences are small and probably only temporary.
2. Post - mortem destruction of tests.
3. Redistribution of tests by currents etc. resulting in either:
    a) The removal of tests so that species have a lower relative abundance than in the living population.
    b) Introduction of tests from adjacent environments.
    c) Introduction of exotic species from farther afield.
4. A relatively recent change in the composition of the fauna, possibly in response to an environmental change.
5. Reworking of old delta deposits.