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BOTTOM SEDIMENTS OF THE RIA DE AROSA (GALICIA, NW SPAIN)

BY

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SUMMARY

The subject of this study is the largest of the 'classical' rias in W. Galicia, the Ria de Arosa (length 25 km, depths of over 65 m). The bottom of the ria displays a complex topography. The wide variety of the surrounding rock types results in the supply of heavy minerals and clay minerals of a variegated composition.

The different types of sediment occurring in the bay are described. The results of various laboratory analyses of some 400 grab samples form the basis of the discussions, but punch-core and boring samples were also studied. The present sedimentary processes are inferred from data obtained from textural and petrographical analyses in combination with the oceanographical and biological characteristics of the ria.

Two types of bioclasts are distinguished: lithothamnion rudite and shell debris. Accumulations of *Lithothamnion* (two species) are restricted to shallow areas, where they sometimes constitute the entire sediment. The innermost part of the ria lacks calcareous algae; the depth-limit of growth shifts downward on approaching the Atlantic Ocean. Shell debris is found throughout the ria, the amount increasing in the direction of the ocean. Accumulations of shell debris are also encountered in shallow areas. The moderate sorting and the absence of a dominant species in the heavy-mineral association of the samples taken in the bed of the largest river flowing into the ria (the Ulla), indicate that these sediments are not in equilibrium with their present environment. This also accounts for the pebbly sands of the Umia River, the second most important confluent to the ria. The rivers supply sandy particles to the ria only occasionally.

Coarse-grained sediments, mainly restricted to the coastal zones, derive from the local bedrock. The distributional boundaries of the eight heavy-mineral associations distinguished in the Ria de Arosa reflect local petrological differences on the mainland, thus indicating the insignificance of long-shore currents. One metamorphic association is exceptional, because the adjoining bedrock is an intrusive granite. The origin of this — presumably relict — sediment found along part of the eastern coast remains a problem. Immaturity of the sandy sediments is confirmed by roundness and quartz/feldspar ratios.

Muds and sandy muds are the predominating types of bottom sediments in the Ria de Arosa. Black liquid muds, smelling strongly of hydrogen sulphide, are encountered in the inner part of the ria. Greenish-grey firm inodoriferous muds are found in the central and outer regions. These physical differences are caused by the decrease in both the oxygen content and the velocity of the bottom current flowing into the ria.

This water circulation pattern also governs the distribution of the clay minerals. The muds are only partially supplied by the rivers, which carry kaolinite, illite, gibbsite, and other minerals. Marine clay minerals, also consisting mainly of kaolinite and illite but characterized by the additional presence of montmorillonite, are brought into the ria by bottom currents.

CONTENTS

INTRODUCTION

Detailed studies of recent sediments are being undertaken at many places to obtain criteria for the interpretation of ancient deposits and the reconstruction of paleoenvironments. The processes by which recent marine and estuarine sediments accumulate can be better understood if the results of sediment analyses are backed by oceanographical and biological data of the depositional environment. With this in mind, a group of scientists in The Netherlands undertook an investigation of the Ria de Arosa (Galicia, NW Spain). The Ria de Arosa was also selected for this purpose because it is surrounded by granites weathering into feldspathic sands and kaolinitic clays, and it was thought worth-while to investigate the extent to which these conditions are reflected in the bottom and beach deposits.

With financial support from The Netherlands Organization for the Advancement of Pure Research

(Z.W.O.), a combined expedition visited the area during the summers of 1962—1964; the scope of the work of the various participants has been summarized by Brongersma & Pannekoek (1966).
Field work was supervised by Dr. J. D. de Jong. Sampling of the bottom sediments was carried out by the author, initially under the direction of Dr. W. J. Sluiter. The present report gives the results of the examination of these samples. The first chapters comprise some introductory remarks, details on the bottom configuration, and an account of the techniques applied. A general survey of the sediment pattern of the Ria de Arosa in the fifth chapter is followed by a description of the different types of sediment in Chapters VI, VII and VIII. The last chapter gives the main conclusions drawn from the study.

ACKNOWLEDGEMENTS

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The valuable discussions with Dr. P. Hartman and Mr. R. O. Felius on clay-mineralogical problems are very gratefully acknowledged. Many thanks are also due to Dr. D. H. Porrenga, Mr. A. Verhoorn, and Mr. R. O. Felius for their clay-mineral identifications and the performance of some analyses. Most of the other analyses were executed in the sedimentological laboratory under the direction of Miss E. van der Wilk; the author's gratitude includes her many collaborators. Dr. A. H. Bouma, then at the University of Utrecht, showed much interest in these investigations. The entire manuscript was read and criticized by Prof. A. J. Pannekoek and Dr. J. D. de Jong and parts of it by Dr. P. Hartman, to all of whom the author wishes to express his sincere thanks for their beneficial advice. Several suggestions to the text made by Mr. P. J. C. Nagtegaal are gratefully acknowledged. Many thanks are also due to Mrs. I. Seeger-Wolf for her reading of the English text, to Mr. B. G. Henning for the preparation of the drawings, and to Miss P. H. Bitter, who typed the tables.

CHAPTER I

PHYSIOGRAPHY OF THE RIA DE AROSA AREA

SITUATION OF THE AREA

The so-called 'Rias Bajas' are four bays on the west coast of Galicia, all running roughly in a NE-SW direction. The largest of these bays, which lies on the boundary between the provinces of La Coruña and Pontevedra, is the Ria de Arosa (Pannekoek 1966 a & b, Fig. 1), shown on topographical maps nos. 151 and 152 issued by the Instituto Geográfica y Catastral de España.
The Carta de la Ría de Arosa, no. 924, Sección de Hidrografía, Madrid (engraved 1915, latest corrected edition 1959) on a 1 : 41,700 scale, containing bathymetric contours, was widely used during our work for the purpose of position finding.

THE CONCEPT RIA

The Ria de Arosa is one of the 'classical' rias, since it was as early as 1886 that Von Richthofen introduced this geological entity on the basis of a description of the Galician examples. Numerous geomorphologists have since put forward theories on the genesis of rias, as recently summarized by Pannekoek (1966 a & b). The Galician rias are by no means unique, this type of bay being found in many parts of the world. Rias recently described by others include occurrences in Brittany (Boysse 1966), Corsica (Schülke 1967), Japan (Hoshino 1964), and Australia (Conaghan 1966).

GENERAL TOPOGRAPHY

The general aspect of the Ria de Arosa is that of a drowned wide valley system, now a broad bay with a water surface of more than 250 square kilometres and depths of over 65 metres. The combined effects of the tectonism of different ages, the diversity of the surrounding petrology, the various forms of weathering of these rocks, and the eustatic changes of the sea-level in Quaternary times, gave the ria its present form.
A monograph on the geomorphology of Galicia as a whole, including the Ria de Arosa, has recently been published by Nonn (1966). For details on the morphology of the surroundings of the ria, the reader is referred to Pannekoek (1966b). Here, only some remarks necessary for a better understanding of the distributional pattern of the bottom sediments will be given.
The fluviatile aspect of the inner part of the ria is soon lost in the further course of the ria. The NW and SE coasts exhibit conspicuous differences, the former showing frequent alternation of rock types of different weathering resistance, the latter being the seaward edge of an extensive granitic landscape. The land on the SE side of the ria, with its low areas around small hills often overlain with thick slope deposits and colluvia, approaches the waterline in gentle slopes which continue under water. This coastline is generally angular and is interrupted by small

estuaries; the NW coast displays broad curves enclosing secondary bays. This type of bay is also called 'ria' if a river enters at the upper end; otherwise, it is called an *ensenada.*

These secondary bays are at least partly controlled by structure. The Ensenada de la Merced, with a SW-NE direction, runs parallel to a Hercynian fault in this direction (Nonn 1966, p. 330) and to the SE flank of the Barbanza massif, which, according to Carlé (1947), Birot & Solé Sabaris (1954), and Pannekoek (1966 a & b), may have originated from Tertiary fault movements. The Ria de Abanqueiro has a NNW direction, roughly in line with a presumed fracture (fault) N of the Ria de Muros y Noya (Nonn 1966, Plate 4).

Although the general trend of the ria was determined by the course of the Ulla River in glacial times and the modelling of the curved coastline must have taken place during the transgressive phases of the eustatic history (Nonn 1964), the shape of parts of the coast may have been determined locally by Hercynian and perhaps by Tertiary structures.

On a local scale, recent processes have altered the coastline in some places. The time at which the largest island, now forming the Peninsula del Grove, became connected with the mainland is not known. Information provided by old maps (1693, 1751) is unreliable, because they show too few details. A much wider tombolo than the present one is shown on a Spanish map of 1793 by Vicente Tofiño. On nineteenth-century maps (1804, 1823) the tombolo acquires more resemblance to its present form, and it can be inferred that El Grove has been a peninsula for several centuries. The occasional absence of the tombolo on maps in twentieth-century atlases may be ascribed to inaccurate copying.

The narrow link between the Con de Navio and the Isla de Arosa, running perpendicular to the tidal currents, must have filled up soon after the inundation. An old village is situated on the tombolo. The first clear depiction of the (united) island can be seen on the map dating from 1823.

CLIMATE

The climate of the western part of Galicia shows, according to Nonn (1966, p. 37), an 'amalgam of oceanic conditions and subtropical influences'.

The close proximity of the Atlantic Ocean keeps average winter temperatures on the rias coast above 8°C, but due to upwelling cold water at the coast in summer the average temperatures in these months rarely exceed 20°C (Masachs Alavedra 1954, Figs. 4 & 5). The absolute maximum temperatures of this region are the lowest of the Iberian Peninsula (*ibid.,* p. 58).

The average temperature of the surface water during the summers of 1962-1964 was 18°C at the mouth of the Ulla estuary(decreasing to 15°C near the Isla de Salvora; values for the bottom water were 1 to 4°C lower (Cadée 1968, Figs. 2 & 4). Only for the Ria de Vigo is the annual course of the water temperature known. The data in Table 1, taken from Ardré *et al.* (1958), show that there is little difference between air and water temperatures, the maximum difference in August being + 3.2°C and minimum in December — 0.2°C.

The greater part of Galicia has an average annual precipitation of between 1000 and 2000 mm (Masachs Alavedra 1954, coloured map), but these values show wide variation locally. The Nuevo Atlas de España (1961) gives 830 mm for Vigo, but much more for most other places, e.g. 1455 mm for Pontevedra. Rainfall is concentrated in the winter months (Masachs Alavedra 1954, Fig. 13), when there is three times as much as in the summer months, and occurs on more than 150 days per year *(ibid.,* Fig. 15).

Circular movements around the nearly constant high-pressure area around the Azores determine the mainly northern direction of the wind (*ibid.,* Figs. 9 & 10). Stormy winds occasionally come from the SW, however, accompanied by heavy rainfall. These winds are more frequent during the winter months.

HYDROLOGY

Water movement in the Ria de Arosa is controlled by three factors: tidal action, influx of fresh water, and wind.

Spring tide in the ria reaches 3.50 m (Cadée 1968, p. 9). The tidal-current velocities are quite low in most places as a result of the wide seaward entrance: 1.3 km/hr for the water at the surface between El Grove and the Isla de Salvora (Nonn 1966, p. 63) and 1.8 km/hr between the islands of Arosa and Rua (Otto, pers. comm.), where the water must pass through a narrower but deeper passage. But in the area between the Isla de Arosa and the mainland, waters flow in from the N and the S at almost the same time, and for the water near El Vado this figure is only 0.5 km/hr (Nonn 1966, p. 63).

Such conditions are extremely favourable for the accumulation of muddy deposits. In the present study the term estuary is used in its restricted sense for the actual river mouths (Pritchard 1967), but because tidal currents play an essential role in sedimentation

TABLE 1. Ria de Vigo, monthly mean air and water temperatures (°C).

	J	F	M	A	M	J	J	A	S	O	N	D
Air	10.2	11.5	13.0	15.0	17.8	20.0	22.5	22.2	20.6	17.0	15.5	12.6
Water	11.9	11.8	12.3	14.6	15.7	18.7	19.9	19.0	17.5	15.0	14.0	12.8

the whole ria may be called an estuary (Guilcher 1963). An exact figure for the average annual inflow of fresh water is not available, because our observations in the winter of 1964 were done during exceptionally dry weather, but this quantity cannot be of great importance to the whole water-mass of the ria except perhaps occasionally, after short periods of heavy rainfall. Current-velocity measurements gave the following figures for the discharge of the Ulla River, which has a total length of 115 km: 10.8 m^3/sec (summer 1963) and 17.2 m^3/sec (winter 1964). If the drainage area of the Umia River and of all other smaller rivers is taken into account, the total influx of fresh water in the two seasons must have been about 16 m^3/sec and 25½ m^3/sec, respectively (Otto, pers. comm.).
About 17 km upstream from the mouth of the Ulla River (at Puentecesures) fresh water already mixes with salt water at high-water tide. At the mouth, the salinity of the surface water was, in both winter and summer, only about 3 $^0/_{00}$ lower than for the ocean (Cadée 1968, Figs. 6 & 7). The real force moving the water in the ria (particularly during the summer) is the prevailing northerly wind, which slowly drives the surface water in the direction of the ocean, with a slight diversion toward the NW coast under the influence of the Coriolis force. This movement is balanced by a bottom current of cold, deep oceanic water; the difference between the salinities of the bottom waters at the two ends of the ria is only 0.1 $^0/_{00}$ (Cadée 1968, Figs. 8 & 9).
Since the inflow of fresh water is low and the wind is the driving force, the Ria de Arosa can be classified as a wind-driven estuary (Brongersma-Sanders 1965). This concept is particularly important for the understanding of the properties and the distribution of the mud and the clay minerals (see in particular Chapter VIII).
Of local importance is the action of ocean waves, especially with respect to the accumulation of bioclasts. This transport agent will be considered in some detail in Chapters V and VI.

PETROLOGY OF THE SURROUNDINGS

Petrological maps of the surroundings of the Rias Bajas have been published by many petrologists (for a summarization, see Nonn 1966, Figs. 52 & 59).
An outline of the petrological setting of the Ria de Arosa given by Floor (1968), was intended particularly to provide background data for the present study and other sedimentological contributions to this series. Some additional remarks can be found on page 109.
A large part of the Ria de Arosa lies in post-Hercynian granite. Weathering phenomena in these rocks have been described by Bisdom (1967 a & b).

PREVIOUS SEDIMENTOLOGICAL DATA

Information about the distribution of bottom sediments in the Rias Bajas is scanty. Some data on the muddy and gravelly sediments and rocky parts is found on the nautical chart mentioned on page 79. for local parts of the Ria de Arosa. A German chart on a small scale (Atlas der Bodenbeschaffenheit des Meeres, 1943) shows the general sedimentary pattern of all four rias and the adjoining shelf, but because it was designed for the use of submarines in war-time, the rocky parts of the bottom have been exaggerated. A few bottom samples taken on the shelf and within the Ria de Arosa have been described by Llarena (1952); his observations are marred, however, by the highly inaccurate positions of the localities.
Clay minerals and heavy minerals from samples taken from the shelf off the West-Galician coast have been studied by Gonzalez Peña & Perez Mateos (1958). A tentative sketch of the distributional pattern of the bottom sediments of the ria based on the calculations of the initial mud to sand ratios has been published by Cadée (1968, Fig. 15).
A detailed study of the various sediment-petrological properties of the beach sands of the Ria de Vigo has been published by Sainz-Amor (1960, 1962) and by Sainz-Amor & Amoros (1962). A similar study of the beaches of the Ria de Arosa was started by Diez-Taboada; two interim reports (1964, 1965) have not provided much information. The results of a sedimentological study of the beaches on the NW coast of the ria will be published by Arps & Kluyver (1968); references to this article wil be found in Chapter VII.
The sediments of the rivers discharging into the ria have been studied by Bisdom (1965) in the upstream part of the Umia River and have been sampled by the present author in the Ulla River and the estuary of the Umia River. Remarks on the sediments of several minor rivers (Rio Té, Rio Beluso, Rio Coroño, Rio Barbanza) are to be found in Arps & Kluyver (1968).

CHAPTER II

METHODS OF FIELD WORK

SAMPLING

Bottom sampling was carried out with a grab that took roughly 20 cm of the upper layer of the sediment. The rivers were partly sampled by hand. The samples, numbering about 400, were packed in plastic bags and sent to Leiden for analysis. The present study is based mainly on the properties of these samples.
During 1962 and 1963 some 70 punch-cores (diameter 7 cm, maximum length 1 m) were obtained. In 1964, two continuous core profiles (in 50 cm sections) were made before the estuary of the Ulla River up to depths of 10 and 12 m of sediment *(to be referred to

* The author is indebted to Mr. M. van Liere (Geological Survey, Haarlem) for his indispensable technical assistance.

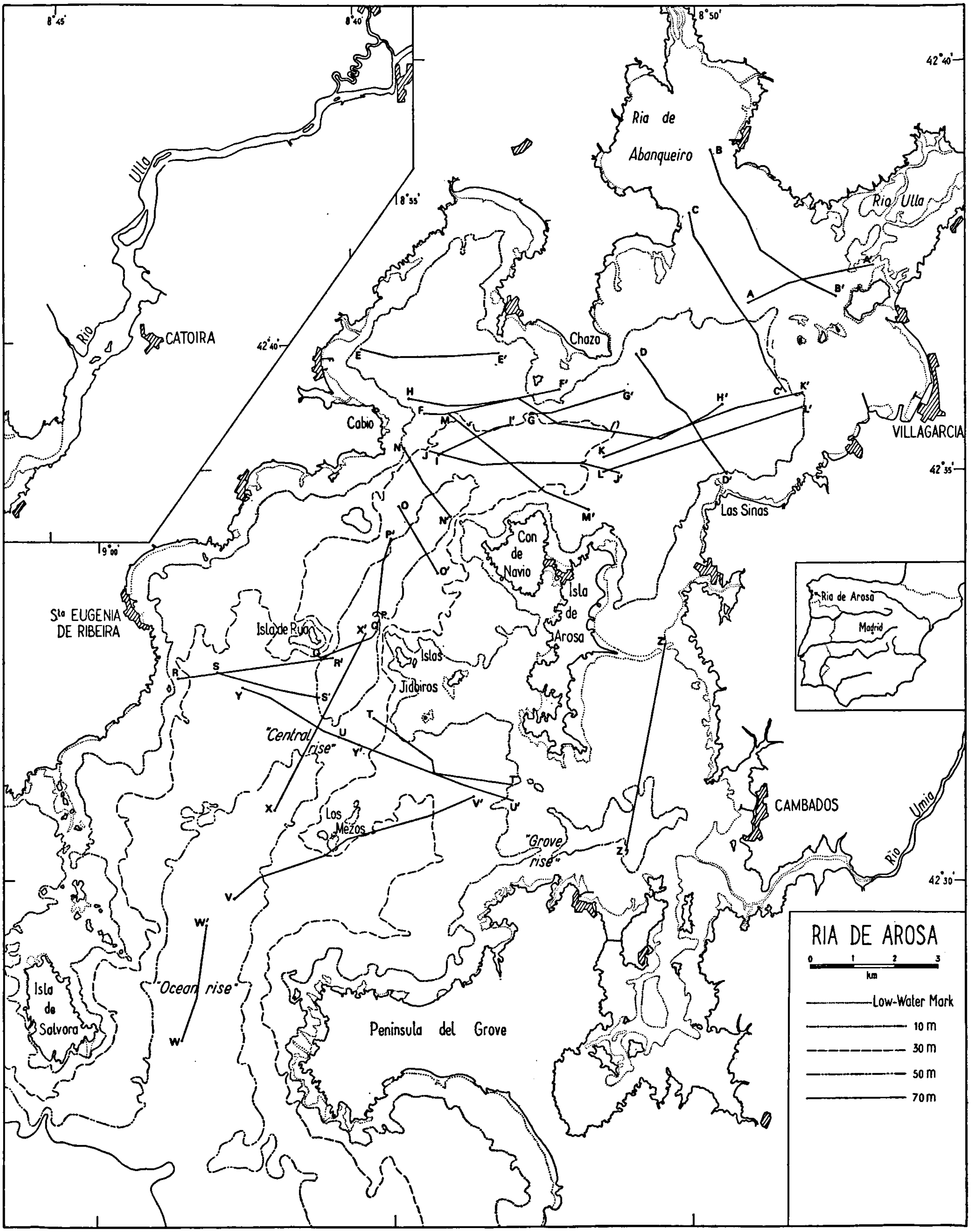


Fig. 1. Locations of echograph tracks.

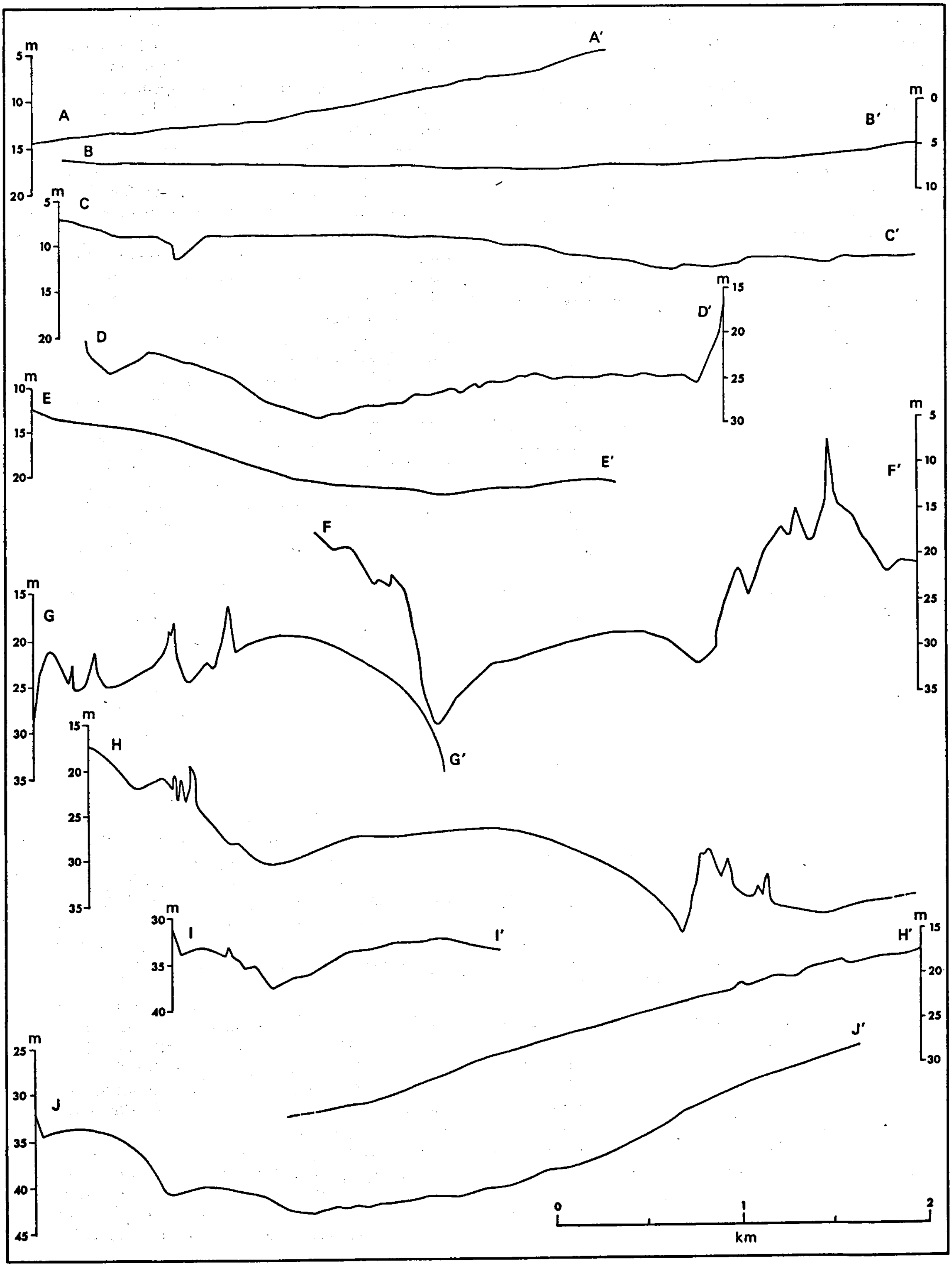


Fig. 2A. Echograph sections of the bottom of the Ria de Arosa.

as deep borings in this study). In the same year a Dachnowski boring apparatus was used in shallow water, yielding 10 borings consisting of continuous series of small samples (diameter 2½ cm, length 17 cm) taken at depths in the sediment of at most 12 m. Because other contributions to these Ria de Arosa publications will deal with the beaches, the present study was restricted to the results of the investigation of all samples taken below the low-water line.

POSITION FINDING

The geographical position of the sampling stations in the ria was determined by using two sextants to measure the two angles between three fixed, well-known points at the same time. The positions were immediately entered on a reprint of the nautical chart mentioned on page 79. This method was found to be satisfactorily accurate; the exact positions would be found to lie within a circle with a radius of 10 m. Accuracy was lower where positions had to be estimated: on the ocean outside the ria and, to a lesser degree, in the secondary bays.
Sedimentological, biological, and oceanographical stations were numbered consecutively in chronological order: 1—205 for the year 1962, 206—536 for 1963, and up to 972 for 1964. All positions can be found on Plate I in Brongersma & Pannekoek (1966); the indication '1.' originally preceding the station numbers has been omitted in the present study to increase readability.

DEPTH MEASUREMENTS

Depths were read in 1962 and 1963 from an echosounder running on batteries. Frequent breakdowns of this small apparatus often compelled us to estimate depth from the length of the cable attached to the grab. A hand-lead was used in shallow water.
In 1964 the Shell Exploration and Production Laboratory (Rijswijk, The Netherlands) granted the loan of a more efficient echosounder for the summer. The sections recorded with this instrument covered a total distance of 175 km. Notwithstanding the fact that the ship on which the echosounder had been installed could not maintain a constant speed, the echograms provided useful information about the bottom configuration in various parts of the ria. Echograms covering a total distance of about 90 km will be discussed in the next chapter.
We were unable to estimate thicknesses of the sedimentary layer because the echograms provided only information about the sediment/water interface. Probably, the duration of the transmitted pulses was not short enough for deeper reflections to be received in this relatively shallow area, depths being less than 100 m. The presence of calcilutite may also have caused difficulties; sections from Boston Harbour subsurface structures are reported to have been completely masked by a thin upper sedimentary layer of black carbonaceous mud (Edgerton & Payson 1964).

CHAPTER III

TOPOGRAPHY OF THE RIA BOTTOM

INTRODUCTION

As we shall see in the following chapters, there are no strong general trends in the distributional pattern of the ria sediments, largely as a result of the complexity of the bottom topography. Hydrology also plays an essential role but is in turn influenced by the local topography.
Since the submergence of the ria, extensive parts of the drowned landscape have been covered with terrigenous and bioclastic sediments of unknown thickness, but in other areas this cover is scanty or absent and residual granitic hills and bare rocks form an underwater landscape similar to the configuration of the mainland (Pannekoek 1966a). A demonstration of the differences in bottom configuration and details on topographic features are given by Figs. 1 and 2, in which 26 tracks and the corresponding sections are shown. Depths are given with a vertical exaggeration of 1 : 50 in all these sections.

INNER PART OF THE RIA

A smooth bottom is found in the innermost part of the ria. The transition between the fluvial deposits in the mouth of the Ulla River and the marine muds is rather abrupt. A delta cannot develop because of the very low transport capacity of the Ulla River. The slope just outside its mouth is relatively steep. The shallowest subaquous part of the Nile delta, for example, has a slope angle of 0°03′ (Dunbar & Rodgers 1957, p. 75), whereas the bottom before the Ulla estuary descends at an angle of 0°10′ over the first 3 km (section AA′).
In all probability, the Ulla River never built out a sandy delta. The deep borings near A and half-way to track AA′ delivered 10 and 12 m uniform mud, respectively. During the last stages of the inundation, waves must have destroyed the original streambed of the Ulla River in this area (cf. Po River; Van Straaten 1965), but could not have been capable of clearing away a pre-existing delta so far within the ria. Centuries of presumably slow but continuous deposition of mud has masked all remaining traces of the river, as demonstrated by cross-sections BB′, CC′, and DD′. Near the western ends, sections CC′ and DD′ show a small gully about 2 m deep. This gully can hardly be a remnant of a tributary, because the former course of

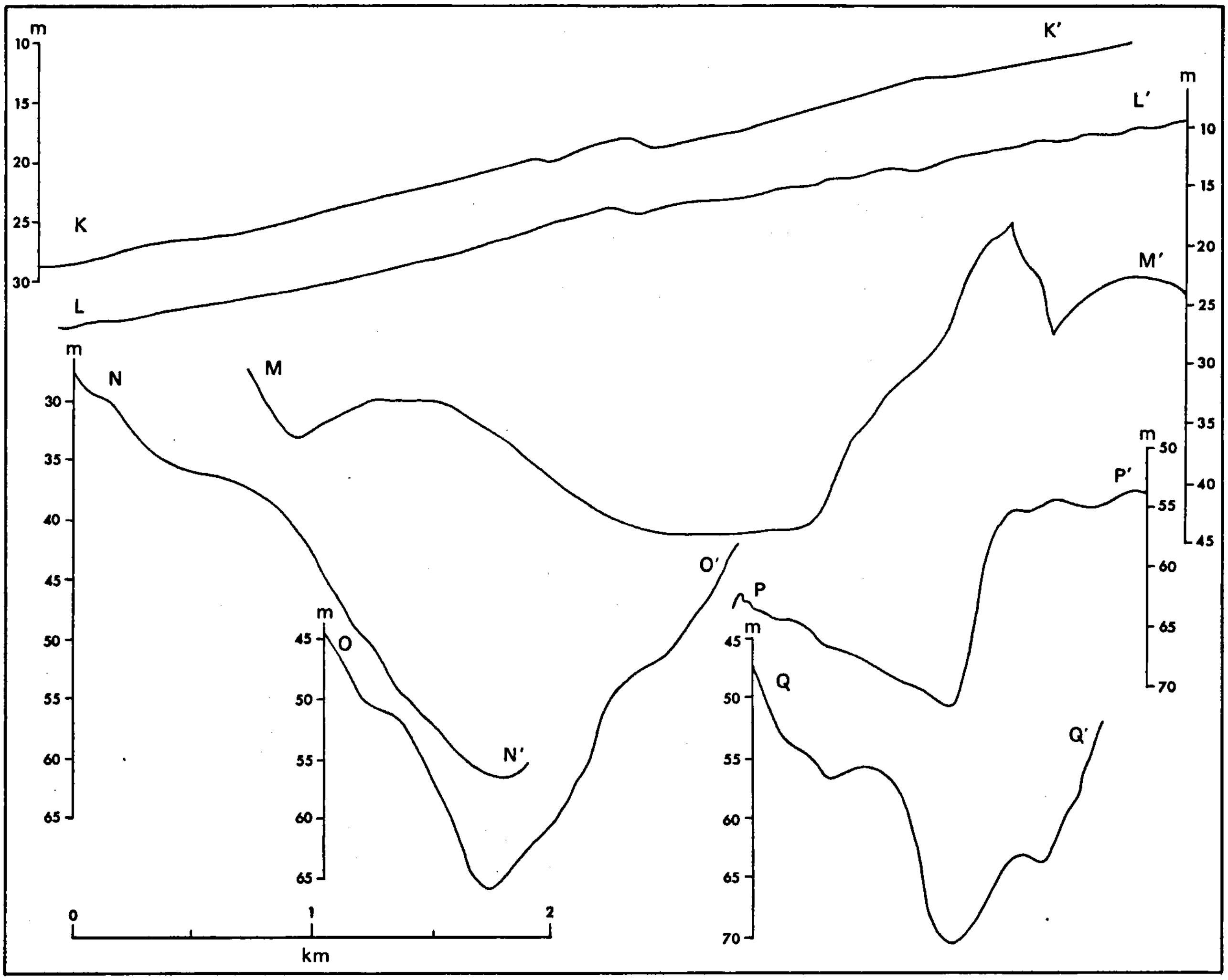


Fig. 2B. Echograph sections of the bottom of the Ria de Arosa.

the Ulla River has itself been completely obliterated. Even smaller gullies can be seen in the eastern part of section HH' and in sections KK' and LL'. It is perhaps better to describe these features as undulations; they are presumably due to tidal currents (Pannekoek 1966b).

The sections in the area Cabio-Chazo-Con de Navio are smooth in their deeper parts but show several peaks at their extremities. Both E of Cabio and SW of Chazo, the bottom consists of a series of residual hills and isolated rocks down to depths of about 25 m. The sediment cover must be thin or patchy in these areas and concentrated mainly in the pockets between the peaks. The configuration of the bottom near the opposite coast is much calmer: the bottom rises quite sharply but smoothly toward the coast near Las Sinas (section DD'); section MM' shows only one broad peak where it passes outside Con de Navio.

CENTRAL PART OF THE RIA

Section MM' shows a very wide depression, but the sections further to the south, in which depths of more than 50 m appear, show an almost symmetrical valley of increasing narrowness: section NN' descends from —40 to —60 m at an angle of 1°30', the western slope of section OO' from —50 tot —65 m at an angle of 2°20', and the western slope of section QQ' from —55 to —70 m at an angle of 4°50'. The eastern slope of these sections is slightly less steep than the western flank. This difference is expressed most clearly in the oblique section PP' and is in accordance with the influence of the Coriolis force on the water mass. In most of the sections mentioned so far, the slopes show bulges on either side. These bulges are not situated at the same depth, however, so an old river terrace may not be assumed. They are more probably expressions of joints in the underlying Caldas granite, now smoothed off by mud deposits.

The deepest point in the ria (about —70 m) is found midway between the Isla de Rua and the westernmost island of the Jidoiros. The bottom rises very slowly from this depression in a northerly direction but ascends more steeply towards the south (section XX'; slope-angle 3°50').

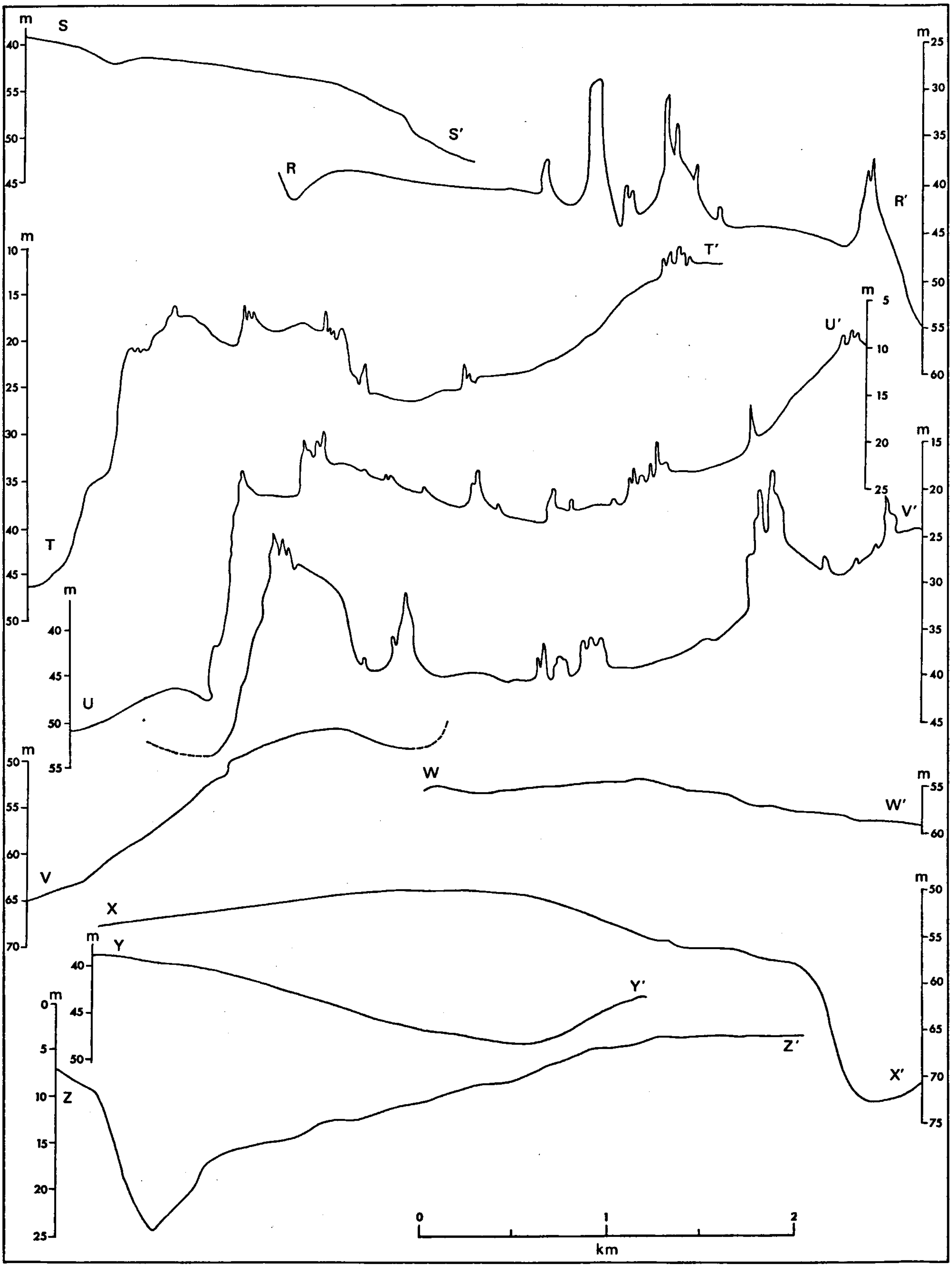


Fig. 2C. Echograph sections of the bottom of the Ria de Arosa.

Whereas the Isla de Rua is more or less the top of an isolated residual hill, the Islas Jidoiros are formed by groups of boulders just barely emerging from the surface of the water. Consideration of the position of these islands and that of the successive sections TT', UU', and VV' yields a picture of a roughly quadrangular block tilted towards the south, its surface consisting of innumerable granitic boulders (not ridges). This bottom, which is completely lacking in weathered granite products and is hardly masked by recent sediments, shows an even more accidented terrain than the corresponding landscape on the mainland (cf. Pannekoek 1966b).

BOTTOM RISES

Rises in the ria bottom are found at three places, indicated on Fig. 1 as 'Central rise', 'Grove rise', and 'Ocean rise'. The last of these is insignificant (see section WW': the bottom is here almost horizontal over several kilometres).

The 'Central rise' was first noticed more than fifty years ago by Scheu (1913), who denied a sedimentary origin because of the lack of transport capacity of the confluents to the ria; he assumed a tectonic origin. However, comparison of sections XX' and YY' shows that the Central rise is saddle-shaped. Moreover, there are no signs of late-Tertiary tectonic events on the mainland, so a sedimentary origin seems likely. We will have to await information about the weathering stage and topography of the bedrock (see page 84) before we can reach a better approximation of the true origin of this rise.

A tentative approach to the problem is to assume a flat dune-ridge near this location during a transgressive phase, when the sea-level was about 50 m lower than at present. The block mentioned above, extending from the Islas Jidoiros to Los Mezos, points to the presence of a relatively resistant type of granite just beside the Central rise. The former Ulla River may at that time have entered the ocean through a narrow passage in this dune-ridge. In its next phase the transgression would have drowned the area and wave action would have redistributed the sediments, after which, of course, the passage would have filled up quickly. Some sandy material must necessarily have been washed into the depression to the north, which would then have been much deeper than it is at present. This concept is supported by the fact that the whole area now lies under a mud cover; two cores taken from the Central rise contained 85 cm of uniform mud (visual inspection and X-ray photos).

The depth-contours at the Grove rise show a resemblance to those near the Traverse de l'Hôpital in the inner part of the ria of Brest in France (Guilcher & Pruleau 1963, Guilcher 1964). Guilcher assumed a pre-Flandrian meander, now largely filled up with sediment; this is at present a shallow area (5—15 m) covered with coarse-grained sands. The Umia River may have had a sinusoidal course at the present Grove rise — not, however, produced by meandering but determined by the presence of hills of relatively resistant granite. In glacial times the course of the Umia River lay at least 25 m lower than the present bed (see section ZZ'). Since information about the basic rock is lacking, we must provisionally assume the same origin for the Grove rise as for the Central rise.

CHAPTER IV

LABORATORY INVESTIGATIONS

METHODS

After the general determination of their coarseness, colour, and odour, the bottom samples were subjected to all or part of the standard treatment outlined in Fig. 3. In this diagram the fractions obtained after a specific treatment are enclosed in rectangles. Resulting data and fractions ready for detailed examination are indicated by rectangles with rounded corners.

The dry residue after removal of the organic matter and soluble salts (quantity estimated by weight loss) is referred to as 'total' sample. This rather inappropriate term was chosen to distinguish samples not treated with hydrochloric acid. The carbonate content was determined separately by titration.

The grain-size distributions of both the total samples and the non-calcareous fractions were determined by a combined pipette-sieve method (Milner 1962a; pp. 158 and 174, resp.). A Robinson pipette was used to obtain the clay fraction (smaller than 2 microns) and three silt fractions (32—16, 16—8, and 8—2 microns). Fifteen sieve fractions ranging between 11,560 and 16 microns were obtained after 10 minutes in a Ro-Tap shaking machine, the pan under the set of sieves collecting the 50—16 microns fraction. Conversion of the overlap into the coarse silt fractions (50—32 and 32—16 microns) introduced an error having a variable influence on the grain-size distribution. The 19 fractions resulting from the combined method are listed in Table I.

The grain-size distribution of the bioclastic fraction was calculated by subtracting the weight percentages of the non-calcareous fractions from those of the total sample. This was only possible for those samples with a carbonate content of between about 20 and 80%; beyond these limits the weight percentages of either the non-calcareous or the bioclastic fractions were too small to provide reliable results.

To obtain some idea of differences in the hydraulic behaviour of quartz sand, shell debris, and calcareous algae, the differential settling velocity of particles of these three components was measured. A settling tube with a height of 1 m and a diameter of 10 cm was

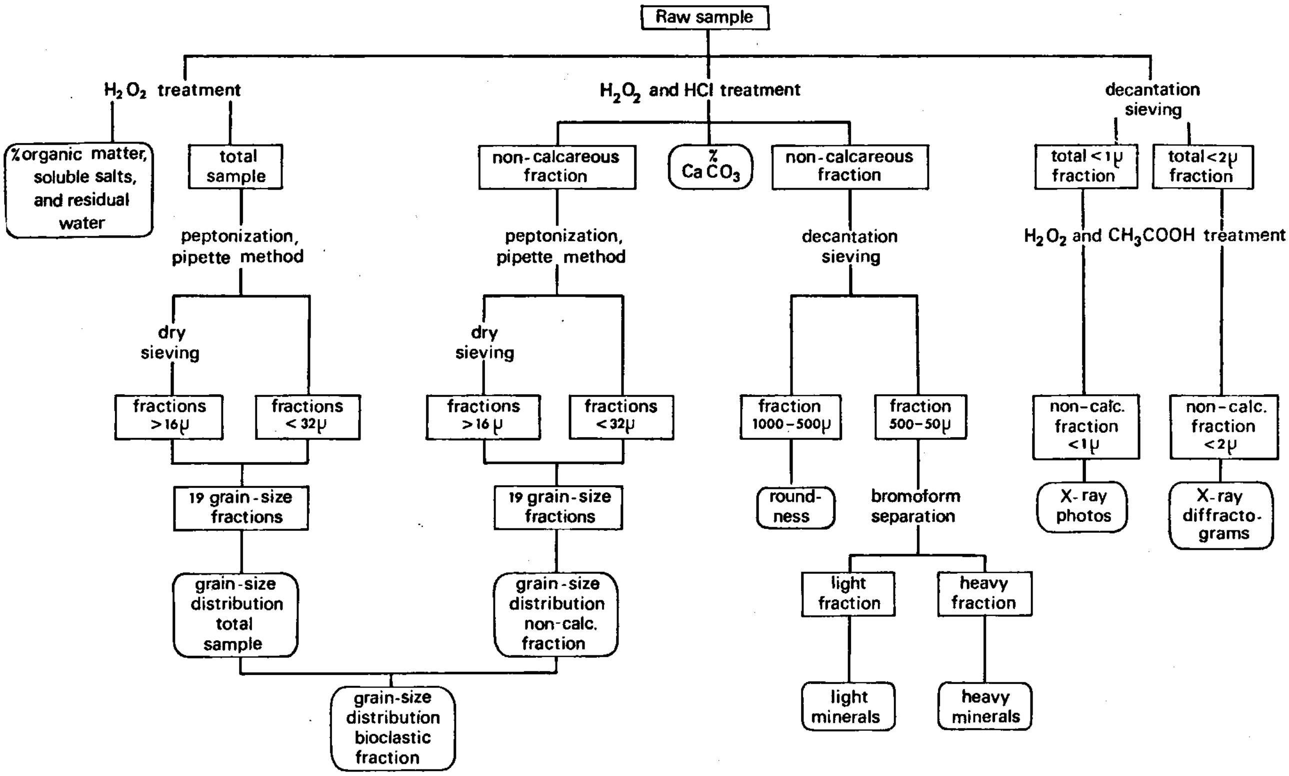


Fig. 3. Flow diagram of laboratory analyses.

filled with distilled water (20°C) into which NaCl had been dissolved to approximate the viscosity of sea water. The settling-time over a vertical distance of 90 cm was determined for 100 particles of each grain-size fraction coarser than 300 microns. In this way the mean settling velocity of nine fractions was obtained for the three components.

Separation of the heavy and light fractions was done in bromoform (Milner 1962a, p. 113). The identification of heavy minerals smaller than 50 microns and coarser than 500 microns is time-consuming and often unreliable. Moreover, grains smaller than 50 microns are very difficult to separate. Therefore, the 500—50 microns fraction was chosen, notwithstanding the fact that the granulometric optimum of heavy minerals generally lies between 350 and 20 microns (Brajnikov 1944). Light-mineral slides were made after embedding the grains in Lakeside (Vogel 1965). Heavy minerals were mounted in Canada balsam (Edelman 1938).

The reader is referred to Chapter VIII for technical data on the X-ray camera and the X-ray diffractometer used in this study. A chemical analysis was made of some decalcified clays.

GRAIN-SIZE DATA AND TERMINOLOGY

The boundaries of the grain-size fractions were converted to the phi-scale (Krumbein 1934). Moment measures according to Friedman (1962) were then computed to provide a characterization of the grain-size distribution of the individual samples. The reasons for using these statistical measures have been summarized in another paper (Koldijk 1968), in which the computer program (in PL/1) can also be found; a Fortran program has been published by Uras & Tamburrini (1966).

Table II lists the formulae and symbols together with the classification of moment measures, and is given as an enclosure to facilitate the reading of the sections on granulometrics. The grain-size fractions originally obtained are expressed in microns. Accordingly, where the mean grain-size is mentioned in sections other than those treating grain-size questions, Friedman's phi-mean is converted into micron-mean ($\bar{x}_\varphi$ into $\bar{x}$; Page 1955).

For descriptive purposes, the sand-silt-clay triangular diagram of Shepard (1954) is the most commonly used graphical classification of sediments. However, sediments with more than 50% clay but poor in silt (or more than 50% silt but poor in clay) occur so rarely in marine sediments that these fields in the diagram are generally unoccupied (cf. Curray 1960a, Venkataratnam 1965). If these fields are reduced, the central part of the diagram becomes too large. Link (1966) proposed a subdivision of the enlarged central field into six parts, but had to introduce unmanageable names such as sandy-silt clay and clayey-silt sand. In the present study, clay and silt percentages are added up and mud is taken as an end-member. Shepard's triangular diagram with mud-sand-pebbles as end-members is widely used (Guilcher & Pruleau 1963). With respect to the physical properties of fine-grained sediments, a 10%-boundary for the mud content seems preferable to the 25%-lines used in Shepard's diagram. A fine sand with a muddy component of say 15% already behaves as a muddy sediment, since it hardens when it dries (Guilcher 1963) and the porosity decreases markedly (Sander 1967). Therefore, a modification of the triangular diagram of Folk (1954) was chosen for the present study (Fig. 5). An additional advantage of this diagram is the possibility of differentiating poorly sorted sediments without giving them awkward names. The term mixtum, introduced by Schermerhorn (1966) for unconsolidated sediments comprising a very wide range of grain-size classes, will be used in this report.

The sediments of the Ria de Arosa are made up of bioclasts and terrigenous detritus, according to the classification of carbonate rocks by Sander (1967). Part of the local terrigenous detritus derives directly from the land around the ria area, but another part may have been in the oceanic environment for quite a long time first and was then resuspended (or was still in suspension) and eventually deposited in the ria. Therefore, 'non-calcareous' fraction appears to serve better as a general term here than terrigenous detritus. The bioclastic fraction can be distinguished into two groups according to the organisms or organic remains involved: lithothamnion rudite and shell debris. The coarse and the fine fractions of the non-calcareous fraction will be treated separately in the following chapters, mainly because of differences in the petrological methods applied.

CHAPTER V

DISTRIBUTION OF THE BOTTOM SEDIMENTS

GENERAL DISTRIBUTION

The bioclastic fraction of the ria sediments has two main components. Calcareous algae form an important constituent of the bottom sediment in several relatively shallow areas, sometimes amounting to 100%. Because of its prevailing grain-size (mainly from 1 to 10 mm) the general term used throughout this study for this type of sediment is lithothamnion rudite. The other bioclastic component consists of shells and shelly fragments of almost all grain-sizes (mainly from 50 microns to 5 mm), and is called shell debris.

Most publications on recent sediments contain some kind of contour map showing the accurate percentages of total carbonate content. A different approach has been used in the present study, because the widely differing ecological, physical, and sedimentational properties make a separate presentation of the distribution of the two bioclastic types desirable. The carbonate percentages of the sediment at most of the sampling stations were determined to an accuracy of 5%. In all samples the relative abundance of the two types of bioclasts was estimated. Plate 1, which is based on these data, shows the distribution of both shell debris and lithothamnion rudite, and the legend gives the key to the total carbonate content.

To avoid confusion, differentiation of the non-calcareous fraction is not indicated on Plate 1. It is important, however, to know for each area the grain-size of the non-calcareous fraction mixed with the bioclasts at that place. These grain-size types are shown in Fig. 4, in which the samples for which the grain-size distribution was determined are plotted (symbols according to Fig. 5); fine and coarse mixtums do not occur in the non-calcareous fraction. Boundaries of coherent areas of muds, sandy muds, and muddy sands are based on these values combined with field observations.

The letter R in Fig. 4 indicates places where submerged rocks without sediment cover occur. Two areas crowded with this letter are conspicuous: the island-arc from La Covasa to the Isla de Salvora, and the area SW of the Isla de Arosa. Bare rocks are so numerous in these areas that the distribution of sediment is patchy. Places where the non-calcareous fraction is almost absent are marked C.

A general trend in estuarine sediments is the high carbonate content of coarse-grained samples and the lower carbonate content with decreasing grain-size (Guilcher 1964, Cotton *et al.* 1965, Vanney 1965). This also holds for the Ria de Arosa. The numbers for 't.s.' in Table 2 give the average carbonate percentages of the total samples having a mean grain-size falling within the phi-range directly above (two averages have been placed between brackets because both are based on two samples only).

Quite another question is whether the carbonate content also changes in the same way with decreasing or increasing grain-size of the non-calcareous fraction. Comparison of Plate 1 and Fig. 4 shows that the extensive area of low carbonate content falls roughly

TABLE 2. Average carbonate contents of total samples and non-calcareous fractions.

mean	1	1—3	3—5	5—7	7—8	8	phi
t.s.	71.2	57.2	37.9	(21.2)	(10.1)	—	%
n.c.f.	39.2	37.3	23.4	44.2	19.6	10.2	%

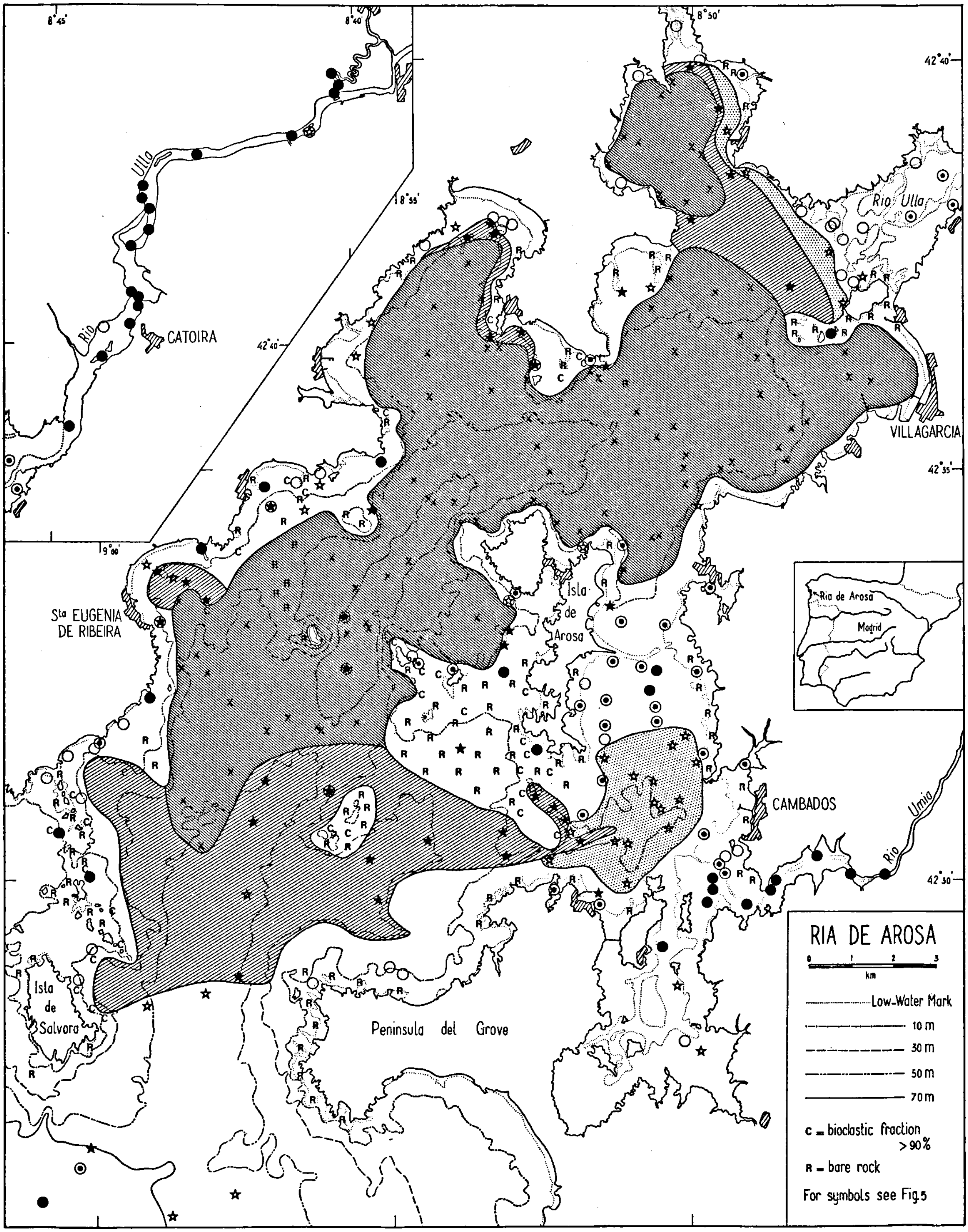


Fig. 4. Distribution of the non-calcareous fraction.

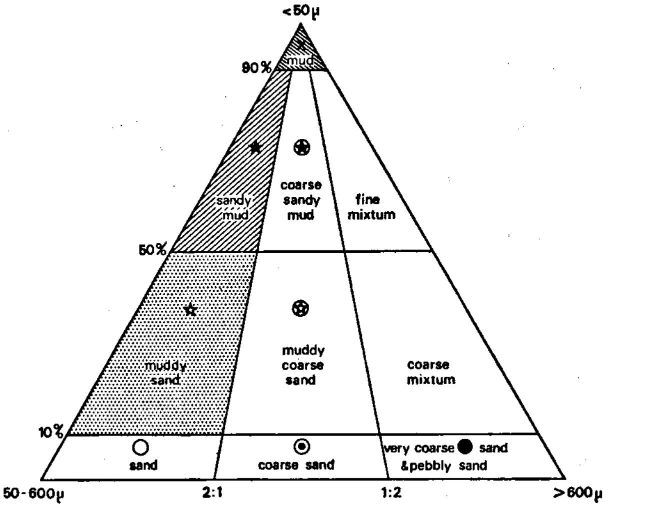


Fig. 5. Triangular grain-size diagram (modified after Folk 1954).

in fields covered with muds and sandy muds. Places with muddy sands and coarser sediments, however, cannot be related to areas of proportionally increasing carbonate content. This is also demonstrated by the average carbonate percentages for 'n.c.f.' in Table 2. Averages are low for very fine non-calcareous sediment-fractions, but there is no regularity in the values corresponding to means greater than +7 phi.

The bioclastic fraction is only an accessory component of the sediment above the low-water line. Most beach sands of the ria contain less than 1% carbonates (Diez Taboada 1964).

LITHOTHAMNION RUDITE

A recent publication of Van den Hoek & Donze (1967) gives a comparison of the distribution of calcareous algae in 11 areas of Europe. The largest numbers of species were found in two regions, viz. northwestern Brittany (France) and northwestern Spain. Consequently, optimum conditions for the development of algal floras appear to be present in these ria areas. Two species of calcareous algae have been encountered in the Ria de Arosa: *Lithothamnion calcareum* and *L. corrallinoides* (Donze, pers.comm.). Live specimens are a vivid red; dead lithothamnion rudite is yellowish-brown. The composition is not pure calcite as stated by Pettijohn (1957, p. 221); chemical analysis of powdered material gave 43.23% CaO and 7.25% MgO. *Lithothamnion corrallinoides* grows mainly free on the bottom and occurs as loose fragments of a repeatedly branched slender type, usually on muddy sediments. *L. calcareum* grows on rocks and coarse sediments but is very easily detached or broken. Its general shape as found in the grab samples is coarser and less branched than the former species, and the branches are thicker: knotted lumps with a diameter of 1 cm or more were found at several places. Encrustations are rare.

The two species have not been distinguished on Plate 1, but an indication of their distribution is given by the granular distribution of the non-calcareous fraction in Fig. 4. Grain-size statistics confirm the difference in particle size of the two species: the average size of lithothamnion rudite in 4 samples of muddy sediment was 970 microns and in 6 samples of sandy and coarse sandy sediments 3050 microns. More details on the various green and red algae in the Ria de Arosa and their distribution will be given in a future publication by Van den Hoek & Donze.

The occurrence of lithothamnion rudite is restricted to the coastal waters and other shallow areas, mainly in the central part of the ria. The most exuberant growth is found around the Chazo peninsula, along the NW coast, at the Islas Jidoiros, and S of the Isla de Arosa. The upper growth limit lies everywhere about one metre under the low-water level, but the lowermost limit increases in depth in the direction of the ocean. As Plate 1 shows, lithothamnion rudite does not reach the 10-m line at Chazo, extends to about 20 m south of the Islas Jidoiros, and reaches 30 m south of Sta Eugenia de Ribeira. This distributional pattern is governed by several interfering factors. Johnson (1962) enumerates six ecological factors which we will discuss with respect to their importance in the Ria de Arosa.

Light (1) is indispensable for the photosynthesis of calcareous algae, and is the most important factor. The growth limit of 20 m in the southern part of the ria agrees with the findings of others (Guilcher & Pruleau 1963, Guilcher 1964, Vanney 1965), but the decreasing depth-limit in the ria in the inland direction cannot be explained by this factor because of the general clarity (2) of the water (Cadée 1968, p. 14). The variance in water temperature (3) in the ria is not an important factor either.

The character of the bottom (4) is one of the factors preventing the development of lithothamnion rudite in the inner part of the ria. The mud in this area, extending almost to the low-water level, is extremely soft and whirls up at the slightest bottom current (cf. page 118). Such conditions would be probably even prevent the growth of free-living *L. corrallinoides.* Another limiting factor here is the salinity of the water (5); the pH may closely approach 7 in the inner part of the ria in times of heavy rainfall (cf. Vanney 1965).

The importance of circulation of the water (6) can be inferred from Plate 1. At the Con de Navio, for instance, lithothamnion rudite is only found around the protruding point, being absent at both sides, which are sheltered from the main current. The oxygen supply probably sets a limit at these places.

Excessive wave action, on the other hand, is also unfavourable for the development of calcareous algae, e.g. at the island-arc near the ocean. A clear demonstration of this effect is given by Los Mezos, the submerged rocky area in the sandy mud of the outer part of the ria (see also Fig. 4). The rim of lithothamnion rudite is interrupted at the ocean side. This growth of algae behind banks serving as a protection against strong wave action has also been noted by Müller (1958) for *Lithophyllum* in a small bay of the Gulf of Naples.

Currents in the Ria de Arosa are not strong enough to transport algal fragments to greater depths, as may be concluded from the absence of branch fragments in deeper waters.

SHELL DEBRIS

The Ria de Arosa has a very rich fauna in which molluscs predominate. All classes of the phylum Mollusca are represented, but the Lamellibranchiata and the Gastropoda display the most species and specimens. The distribution of the various molluscs has been reported by Cadée (1968). Other constituents of the bioclastic fraction are fragments of Echinoidea and Crustacea (crabs).

The crushing of shells to debris by mechanical forces is only possible on coasts subjected to strong wave action, i.e. on oceanic coasts with violent breakers (Asensio Amor 1966). This situation exists on the whole West-Galician coast during times of SW storms, which could account for the continuous shell-debris zone running the length of the West-Galician coast (Llarena 1952). The shell debris around the islands between La Covasa and the Isla de Salvora must have derived in large part from this zone during heavy weather. It is impossible to obtain quantitative biological confirmation of this hypothesis, because the fauna of the Atlantic Ocean and the southern part of the ria have so much in common (Cadée, pers. comm.). The wave action at this island-arc prevents the deposition of much shell debris. Deeper water means less movement, and as a result more shell debris may accumulate (Emery *et al.* 1957). Accordingly, the layer of shell debris at the Islas Jidoiros is thicker than that north of the Isla de Salvora. Shell debris entirely surrounds isolated rocks or islands such as Los Mezos and the Isla de Rua. Under stronger wave action the accumulation would take a parabolic form (Vanney 1965), but this is not found even at the rocks near the ocean.

The disintegration process which produces the shell debris within the ria is of a biological nature. The responsible organisms are chiefly borers (algae which minutely perforate living and dead molluscs) and predators (which crush shells of living animals). The resulting grain-size depends on the kind of predator. Consumption of molluscs by fishes (like the plaice) produces very fine fragments, crabs cut shells into corarser fragments, and sea-stars generally force the valves of a mollusc apart without breaking them. For more details, the reader is referred to Cadée (1968, p. 83). A survey of the literature on biological disintegration processes can be found in Swinchatt (1965).

The clay fraction has a very low carbonate content; this is most probably related to the re-use of dissolved carbonates for the building of new shells (Guilcher & Pruleau 1963). Although the boundary between the mudfield and the sandy mudfield in the outer part of the ria (Fig. 4) runs strikingly parallel to the boundary between the fields with 10 to 25% and 25 to 50% shell debris, we do not think that this has any connection with the re-use of calcilutite for new shells. The sandy mud under water with depths over 30 m is only a trifle coarser than the mud to the north (see page 121).

Other ecological factors determine the increasing abundance of life in the direction towards the ocean. These factors, which have been discussed by Cadée (1968, p. 61), all point to a decreasing oxygen content of the bottom water flowing inwards into the ria. The reader is referred to Chapter VIII, where the physical properties of the muddy sediments are discussed in more detail.

NON-CALCAREOUS FRACTION

A comparitive study of eight bays in the southern part of Japan (Mitsushio 1967) has shown that there is a relation between the length/width ratio of a bay and the fineness of its bottom sediments. A high ratio number, i.e. a high degree of embayment, goes with much muddy sediment. The degree of embayment of the Ria de Arosa is 5.4 (25.0/4.6 km) and mud is therefore the dominant type of sediment in the ria.

From the outline of the mud field in Fig. 4 it is evident that the water movement is much more restricted in the inner part of the ria than south of the passage between Cabio and the Con de Navio. The reduced tidal currents allow the deposition of mud in the shallow waters very near the coast. The sedimentology of the whole area covered by muds and sandy muds will be discussed in Chapter VIII.

In the inner part of the ria the type of the bottom sediment changes over a very short distance from beach sands into mud, so that in Fig. 4 no circles indicating sands are found in this area; such circles appear along the other coastal areas and in the Ulla, Beluso, and Umia rivers. The granulometrics and the petrology of these coarse sediments will be discussed in Chapter VII. From Fig. 4 it can already be seen that the grain-size of the Ulla sands gradually decreases toward the mouth, whereas the Umia sands are still very coarse where the river enters the ria.

CHAPTER VI

SEDIMENTOLOGY OF THE BIOCLASTIC FRACTION

DIFFERENCES IN HYDRAULIC BEHAVIOUR

The use of granulometric data from sieve analyses for the interpretation of a sedimentational environment has no value from a hydraulic point of view unless the mineral composition of the sediment is taken into account (Berthois 1965). Hence, it was important for the present study to obtain some idea of the differences in hydraulic behaviour of the bioclastic fraction and quartz sand.

As outlined on page 87, this was achieved by measuring the fall velocity of individual particles of *Lithothamnion calcareum* from sample 172 (in 6 grain-size fractions ranging from 0.85 to 11.56 mm), of shelly fragments of Lamellibranchiata from sample 371 (8 fractions, 0.30 to 6.80 mm), and of quartz grains and quartz/feldspar rock fragments from sample 940 (9 fractions, 0.30 to 11.56 mm). The mean settling velocity values are plotted in Fig. 6 against the midpoints of the grain-size fractions (curves l_3, s_3 and q_3, respectively).

Our fraction boundaries are wide and the method of measurement is rather gross; therefore, the results shown in Fig. 6 are accompanied by some other curves given for reference purposes. Curve q_2 is taken from an accurate study of the settling velocities of natural quartz-grains by Berthois & Gendre (1967). For the sandy fractions our curve q_3 almost coincides with this curve; for the coarser grains in the lower part of the graph, however, the curves diverge. This divergency may be due to the fact that the coarser the particles, the greater the number of rock fragments measured; our grains of the pebble fractions, consisting partly of weathered feldspar, settled more slowly.

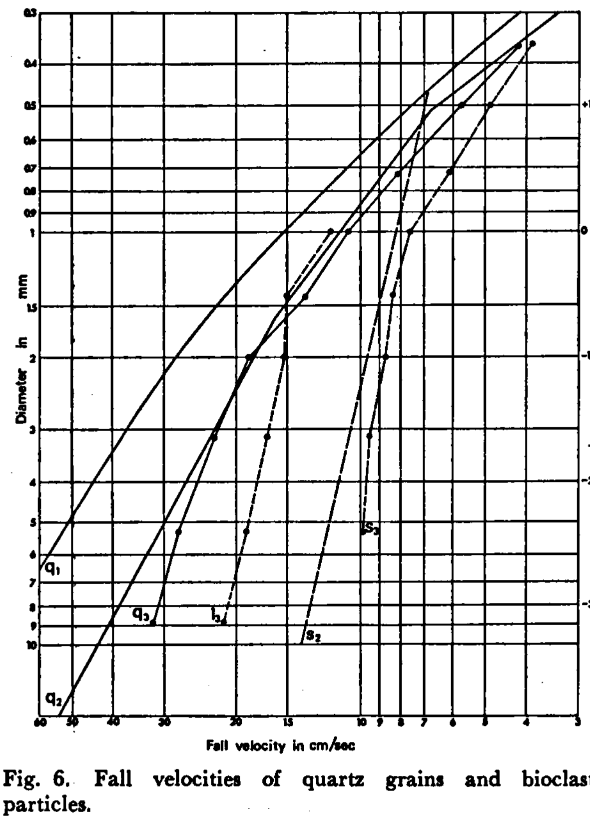


Fig. 6. Fall velocities of quartz grains and bioclastic particles.

q1 — quartz spheres (after Kennedy & Koh 1961).
q2 — quartz grains (after Berthois & Gendre 1967).
q3 — quartz grains (Ria de Arosa).
s2 — shell debris (after Berthois 1965).
s3 — shell debris (Ria de Arosa).
l3 — lithothamnion rudite (Ria de Arosa).

Berthois & Berthois (1955) came to the conclusion that there is little difference between the hydraulic behaviour of natural quartz grains and quartz spheres, but this may not hold for angular quartz grains. Curves q_2 and q_3 both lie definitely to the right (lower fall velocity) of curve q_1 for quartz spheres (after Kennedy & Koh 1961).

The hydraulic behaviour of fragments of Lamellibranchiata has also been studied by Berthois (1965); curve s_2 is borrowed from him. The specific density was determined with a pyknometer, the values being 2.88 in the present study and 2.77 in Berthois' — both approximating the specific density of aragonite (2.94). The fall velocity of this material therefore depends entirely on the shape of the particles. As can be seen from curve s_2, the sphericity of the grains of the Lamellibranchiata investigated by Berthois did not change much with decreasing grain-size. Owing to the low sphericity of the finer grains (often very thin, whole shells) in the present study, curve s_3 bends to the right in the lower grain-size range.

The fall velocity of particles of calcareous algae is determined not only by their shape but also by their internal structure with its numerous pores. Berthois & Guilcher (1959) measured the settling velocities of grains of *Lithothamnion calcareum* occurring in the ria of Brest (Brittany, France). As a result of strong current velocities, the grains in their study were of the 'knotted-lump' type (cf. page 91) and their results cannot be compared with curve l_3 for the branched types prevailing in the Ria de Arosa. In the 2 to 1.5 mm range, branched particles become extremely rare. The changes in fall velocity due to decreasing size and greater sphericity cancel each other out, and therefore curve l_3 remains almost vertical over a short distance. The difference in specific density with respect to quartz is small (2.57 as compared to 2.65). Particles smaller than 1.5 mm behave like quartz grains, so that the upper part of l_3 roughly coincides with q_3.

The transport of individual grains of lithothamnion rudite in the ria is insignificant, but in view of the shell-debris accumulations encountered at several places, Fig. 6 must be kept in mind while reading the following sections. With increasing grain-size the divergence between curves q_3 and s_3 becomes continuously wider. The graph shows, for example, that shell debris with a grain-size of 1 mm may be transported together with quartz grains of about 650 microns; shell debris measuring 5 mm may be found together with quartz grains of 900 microns, and so on.

GRANULOMETRICS OF LITHOTHAMNION RUDITE

Because lithothamnion rudite is found only where the calcareous algae grow at present, the sedimentological properties of this type of bioclast are rather immaterial, and a few brief remarks on the subject will suffice.
Grain-size parameters of some lithothamnion-rich samples are shown in Fig. 7; Fig. 7A gives a graph of standard deviation versus skewness, and Fig. 7B gives a part of the triangular grain-size diagram of the type of Fig. 5. Five samples consist entirely of lithothamnion rudite (square symbols); all of them are pebbly sands with means over —1 phi. The four other samples are coarse mixtums: they contain mud in addition to the algal particles and also a very minor amount of small shells (Gastropoda; Cadée 1968, p. 35). Parameters are given for the grain-size distribution of the total sample (triangles) and for the bioclastic fraction (circles).
Fig. 7 shows in the first place that algal growth

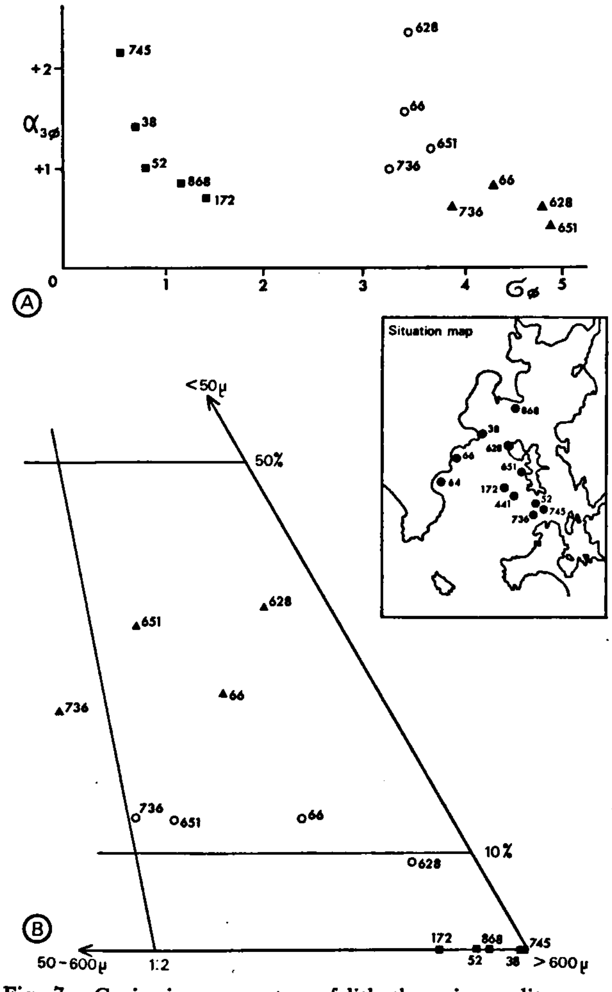


Fig. 7. Grain-size parameters of lithothamnion rudite.

undisturbed by sedimentation of non-calcareous components results in moderately to moderately well sorted deposits (see Table II). The various factors summarized on page 91 determine the maximum local grain-size. The coarsest grains thus have an upper limit, but broken-off parts of branches may occur in many finer size-fractions; this causes the positive skewness of the lithothamnion rudite.
The extreme values of the standard deviation of the total coarse mixtums indicate that the grain-size distribution of these samples is not unimodal. This could be expected in these mixtures of mud with the coarse and positively skewed lithothamnion rudite, and has also been reported from other areas (Berthois & Guilcher 1959, Guilcher & Pruleau 1963, Guilcher 1964). The bioclastic fraction of these samples is more strongly skewed and the plots also lie in the coarse mixtum-field, but a mud content of approximately 10% is still present. The surrounding muds do not contain enough carbonates to account for the mud content of the bioclastic fraction at stations 66, 628, 651, and 736; consequently, this mud must in part be a distintegration product of lithothamnion rudite. It comprises mainly the clay fraction plus the very fine silt fractions (smaller than +6 phi), in contrast to the normal non-calcareous mud (cf. page 88). Apparently, sand-sized algal grains fall apart directly into particles smaller than +6 phi.
Conversely, the absence of fine-grained carbonates at the five stations discussed first, implies that the bioclastic fraction of the muds in deeper water might be partially derived from lithothamnion rudite. This possibility has not been taken into account in Plate 1. Determination of the calcite/aragonite ratio would solve this question only partially, because some constituents of shell debris also consist of calcite (echinoderms, for example).
Our data on the thickness of lithothamnion-rudite accumulations are not numerous because the punch-corer could hardly penetrate this brittle but hard material. At stations 52 and 441 (near the southern point of the Isla de Arosa) the cores contained lithothamnion rudite only, about 30 and 20 cm respectively. Another core, 20 cm long, was obtained at station 66 (Palmeira): lithothamnion rudite forms the upper 13 cm, lying over calcareous muddy sediments. In all three cores only the upper 3 cm appeared to consist of bright red living algae.
A core with a total length of 25 cm was obtained at station 64 (Sta Eugenia de Ribeira); here, the upper 3 cm also consists of the living organisms, but it overlies muddy sediment completely lacking calcareous algae. Apparently, algal growth had just begun at this place.

GRANULOMETRICS OF SHELL DEBRIS

Introductory remarks

Before discussing the textural properties of this bioclastic material, we may pose the question of whether the depositional interpretation of the grain-size parameters of non-calcareous sediments is also applicable

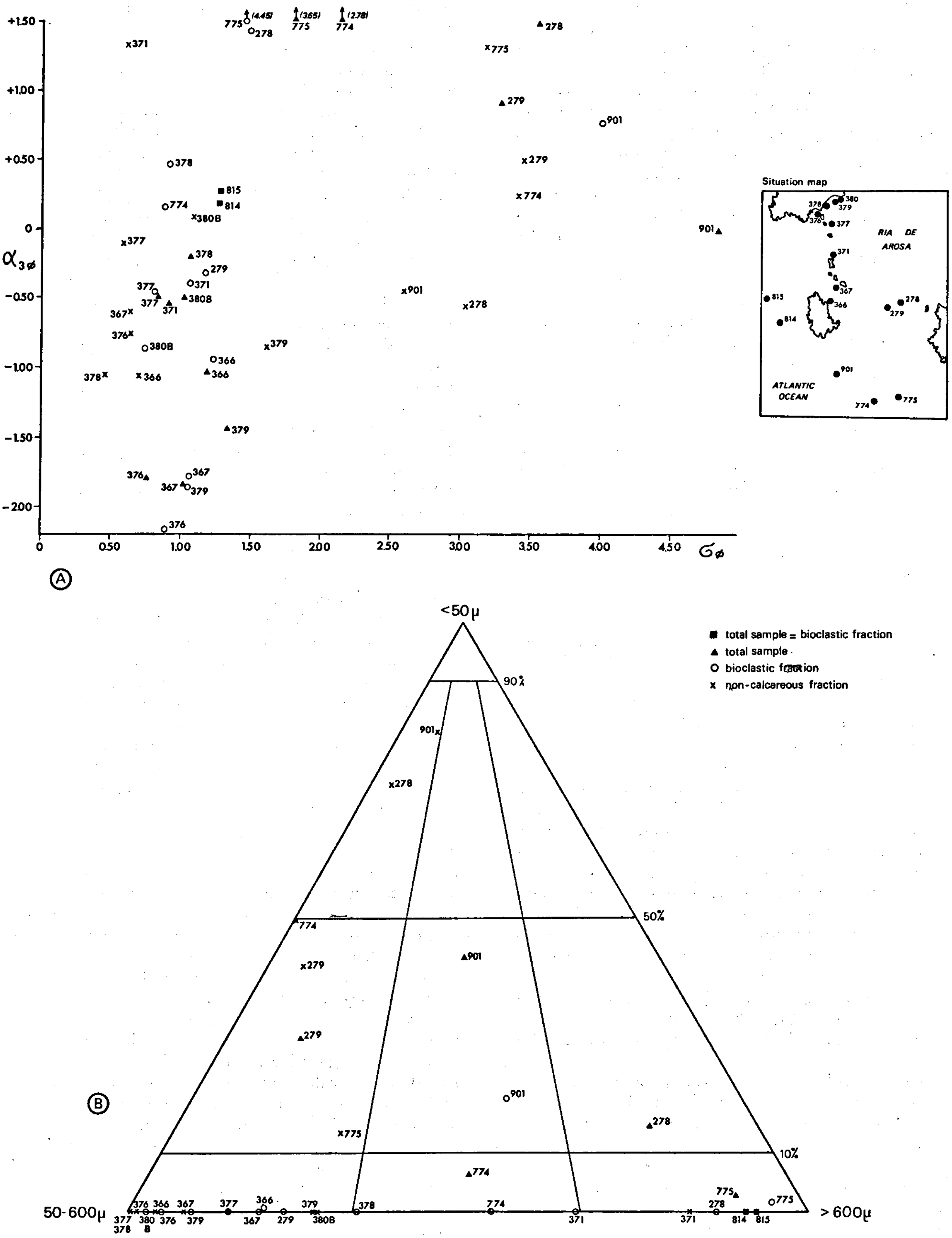


Fig. 8. Grain-size parameters of shell debris; ria mouth.

to accumulations of shell debris. A study comparable to our work has been made by Fuller (1961) around the Cape of Good Hope on marine sediments containing 20 tot 40% shell debris. Cumulative grain-size curves of both the total sample and the bioclastic fraction showed knick-points at the same places, namely at +0.8 phi (compare Fig. 6, curve q_2) and at +2 phi. From these observations Fuller concluded that the behaviour of quartz grains and bioclastic particles was identical. Van Andel (1964, p. 268), on the basis of the fact that the shell debris in the sediments of the Gulf of California is largely if not entirely detritical, went so far as to state that only the grain-size distribution of the total samples need be taken into account.

The difference between the hydraulic behaviour of the non-calcareous fraction and the bioclasts is indeed negligible in the size-range finer than about +1 phi (see Fig. 6). Sediments coarser than about 0 phi show an increasing difference, but also for shell debris (curve s_3) the relation between diameter and settling velocity is linear in Fig. 6. We may therefore state that in the case of the coarse ria sediments: (1) the differences between the curves make it necessary to decalcify the samples, and (2) because both curves are rectilinear, water movement may affect sorting and skewness of the shell debris in the same way as it does the non-calcareous fraction.

Shell debris in the mouth of the ria

On page 92 we made the assumption that the shell debris in the area between La Covasa and the Isla de Salvora derived largely from the ocean. We will therefore first consider samples from this area (see Fig. 8), i.e. numbers 814 and 815, consisting exclusively of shell debris (total sample = bioclastic fraction), eight samples from the island-arc, and five samples taken near the mouth of the ria. Statistical parameters of these samples have been plotted in Fig. 8, A & B, triangles indicating the total sample, circles the bioclastic fraction (squares for 814 and 815), and crosses the non-calcareous fraction. The three different plots for one station in the triangular diagram should lie on a straight line; if they do not do so, this is due to errors in the analysis. The total fraction and the non-calcareous fraction were processed separately (Fig. 3), which introduces a source of error in calculations of the grain-size distribution of the bioclastic fraction. In Fig. 8B only the plots of sample 901 are not exactly in line, probably due to the high mud content.

Samples 814 and 815 are bioclastic pebbly sands. They are only slightly skewed and seem to be moderately sorted (Fig. 8A), but here the standard deviation gives misleading information. The frequency curves are very polymodal and platykurtic (kurtosis about 2); accordingly, the sediment is actually extremely poorly sorted. Stations 814 and 815 are situated at depths of slightly over 60 m; there the sediment is entirely bioclastic, and consequently these samples must have derived from the great zone of shell debris. The data of Llarena (1952) are not sufficiently complete to permit estimation of the depth limits of this zone, but it may well extend 20 to 30 metres deeper. During the glacial maximum toward the end of the last glacial period, the level of the sea was some 120 m lower than it is now (Curray 1965: [Late-Wisconsin] —120 to —125 m; Van Straaten 1965: [Late-Würm] —110 to —120 m). In that period calcareous beach sands, probably skewed and well sorted, may have accumulated in this region. During the first stages of the inundation of the ria, however, the environment changed and the shell debris was redistributed by bottom currents coming from various directions. Low kurtosis values are the result of this redistribution (Cadigan 1961). The force of these currents decreased with increasing water depth, and the random migration of the shells all but ceased when the depth of the water became more than about 20 metres (Van Straaten 1965). The shell-debris zone as we find it today does not lie in its original depositional environment but forms a relict sediment (Curray 1965) with the constituent grains spread almost equally over all grain-size fractions.

All 24 plots of the eight samples from the island-arc lie on the base-line of Fig. 8B; to avoid confusion, the plots for the total samples have been omitted. The plots of sample 371 are found on the right (means about +¼ phi); all other samples and fractions are sands with means between +1½ and +2½ phi. In accordance with this grain-size and with the data in Fig. 6, the three different plots of one sample lie quite close together, the shell debris being a trifle coarser than the non-calcareous fraction. This and the unimodal frequency distributions indicate that the sediment is in equilibrium with its environment. Water movement in the less sheltered area in which station 371 is situated, prevents supply of the coarsest bioclasts, so that the non-calcareous fraction of sample 371 is coarser than its bioclastic fraction. These particles evidently do not reach the northernmost positions (379 and 380B).

From the foregoing we could expect the samples to be moderately to moderately well sorted, which is indeed shown by Fig. 8A. With the exception of the best-sheltered station (378), the bioclastic fractions show their beach environment by a negative skewness. The non-calcareous fraction is supplied by two different transport mechanisms, i.e. by water currents from nearby beaches and by air from dunes on the mainland to the north (cf. page 115). The influence of aeolian sand (positively skewed) is demonstrated by the skewness values of the non-calcareous fractions in Fig. 8A, which are less negative than those of the bioclastic fractions. The relative influence of the two transport mechanisms is expressed, for example, at station 371 (beaches at some distance; strongly positively skewed) and station 378 (near a sheltered beach; in this exceptional case more strongly skewed than the bioclastic fraction).

Summarizing the data of these eight samples, we find: (coarse) sand with abundant shell debris, moderate sorting, sediment alternating with bare rocks, and low supply of terrigenous material. This is a typical example of a calcarenite facies as defined for the Gulf of California by Van Andel (1964, p. 289).

Several extreme values result from the grain-size data of the samples in the southern part of the ria mouth, mainly for the non-calcareous fractions (Fig. 8A). The frequency distributions of the bioclastic fractions are unimodal, with the exception of sample 901. The non-calcareous distributions, however, show two or three modes: in the medium sand and the clay classes, and sometimes also in the very coarse sand class.

Shell debris around the Isla de Arosa

Data of samples taken along the southern part of the Isla de Arosa are shown in Fig. 9, in which the symbols used are the same as those in Fig. 8. The three different plots for one station are generally well in line

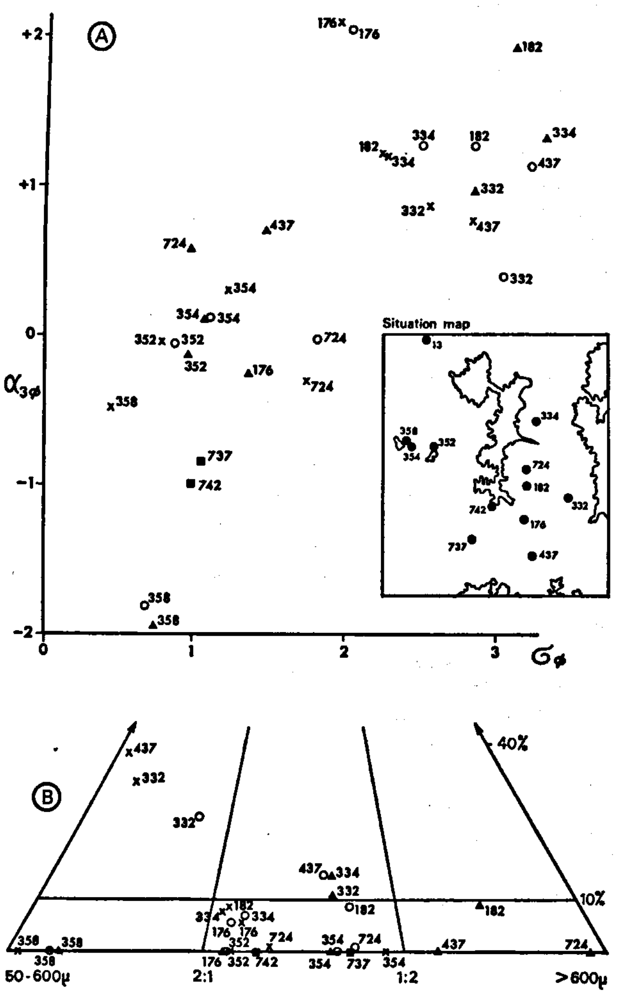


Fig. 9. Grain-size parameters of shell debris; Isla de Arosa.

with each other (Fig. 9B), with the exception of stations 176 and 334, and the latter data must consequently be regarded as rather inaccurate. The data of sample 724 are only approximate, because the bioclastic fraction of the sample actually contained particles over —3½ phi (the limit taken for the calculations).

Unimodal frequency distributions were found for samples 352, 354, and 358 originating from the Islas de Jidoiros; these samples display the characteristics of the calcarenite facies as described above. Because water movement is much more restricted here than along the island-arc near the ocean, the water-depth must have a strong influence on the grain-size parameters of these three samples. This is demonstrated by their skewness values (Fig. 9A): the sand of sample 358 (water depth 2 m) is highly negatively skewed; the coarse sandy samples 352 (4m) and 354 (5) are nearly symmetrical.

Two other, entirely bioclastic, coarse sands are found south of the Isla de Arosa. These samples (737 and 742) were also taken from a shallow, rocky area; they are moderately sorted, have a unimodal frequency distribution, and are negatively skewed.

A different type of sediment is found in the sheltered area E and SE of the Isla de Arosa. Both the bioclastic and the non-calcareous fraction of sample 176 have bimodal distributions and are poorly sorted. The remaining samples have polymodal frequency distributions and generally show extremely poor values for the standard deviation. The differences in the mud content of the samples have no bearing on the variation of the skewness, which is positive for all the fractions and total samples. These textural properties show great resemblance to those of samples 814 and 815, which were taken from the relict sediment on the ocean. We might assume a similar origin for the sediments in the area between the Isla de Arosa and the mainland, but this would require more information, i.e. from petrological data (see page 116).

A few samples with more than 50% mud in the non-calcareous fraction were subjected to separate analyses. The constituent bioclastic fractions are poorly or extremely poorly sorted, positively skewed, and generally fairly platykurtic; there is a great variety in the mean grain-size and mud content. Only the bioclastic fraction of sample 13 (Fig. 9, situation map) is negatively skewed, probably as a result of the abundance of juvenile organisms in this region (Cadée 1968, p. 94). There is no relationship at all either between the degree of coarseness of the two fractions or between the parameters of the bioclastic fraction and the water depth or situation in the ria. We may therefore conclude that there is no marked migration of shell debris in the muddy regions of the Ria de Arosa. The bioclastic fraction is the local biological disintegration product.

CHAPTER VII

SEDIMENTOLOGY OF THE NON-CALCAREOUS COARSE FRACTION

GRAIN-SIZE DISTRIBUTION

Introductory remarks

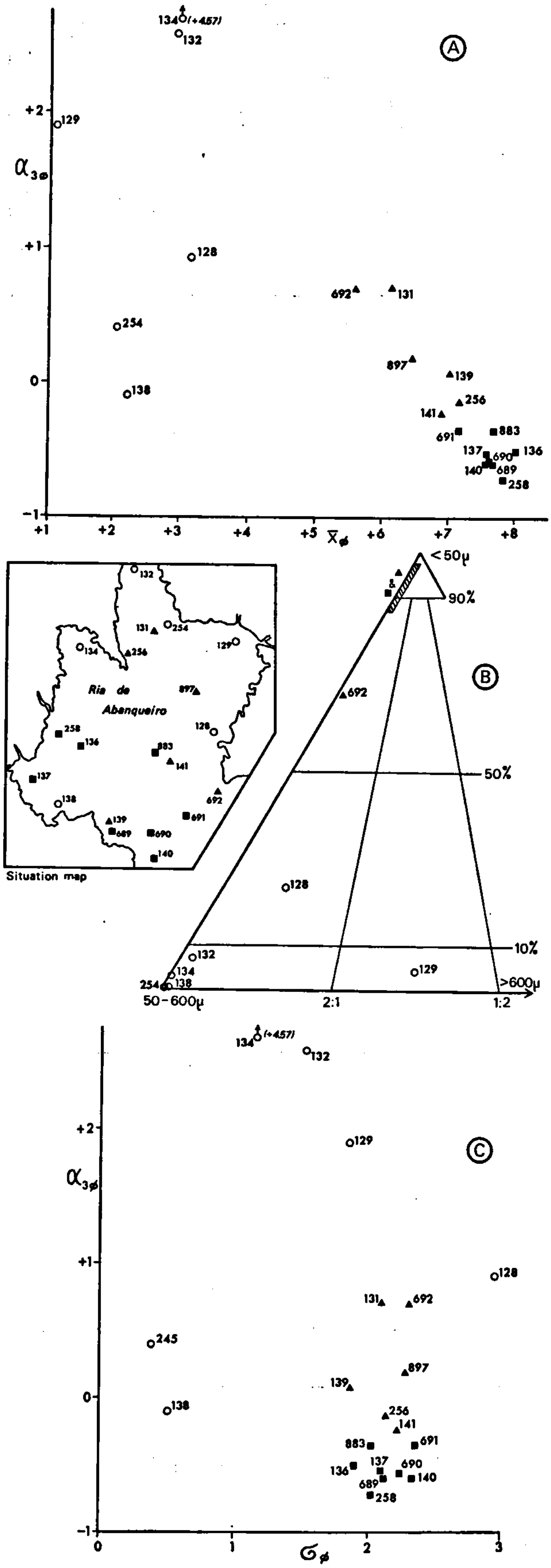
This section is primarily concerned with sands and coarser material, although mud is seldom absent from these samples, which leads to difficulties in the application of moment measures.
The reader will be aware of the fact that all grain-size fractions are involved in the calculation of moment measures and that the mid-point of each fraction is charged with the corresponding weight percentage (Friedman 1961, 1962). In muddy sediments the lower boundary of the finest class is unknown. Friedman (1965, 1966) suggested that a value of +6 phi be assigned to the fraction smaller than 62 microns (= +4 phi); recently, the same author compared the results obtained by treating the finest fraction both as +4¼ phi and as +6 phi (Friedman 1967). In the present study the weight percentages of four silt fractions were obtained, and clay formed the lowest grain-size class comprising all particles smaller than 2 microns, or +8.97 phi. For a few samples the weight fraction smaller than 1 micron was obtained; in some samples most clay was coarser than 1 micron, in others finer. In our calculations the mid-point of the clay-class has been taken as +9.97 phi, or 1 micron (see Table I).

Ria de Abanqueiro

Although it might seem logical to commence the granulometric description of the ria with the Ulla River, we will consider the Ria de Abanqueiro first because of its close resemblance to the great ria (Fig. 10). This bay is rightly called a 'ria' — it is the Ria de Arosa in miniature. The main confluent, the Beluso River, pours in from the north, and in the south the Ria de Arosa itself represents the ocean. Broad sandy beaches alternate with rocky coastal sections, and the deeper parts of the Ria de Abanqueiro are covered with mud.
Four sands and one coarse sand (Fig. 10B) from this bay were analyzed; they all have unimodal distributions. Sorting and skewness, however, are rather variable due to the absence of transport agents of any importance. An extremely poor standard-deviation value is found for sample 128 (Fig. 10C); this muddy sand has a polymodal frequency distribution, doubtless as a result of dredging being carried out in the harbour of Rianjo.
It can be seen from Fig. 4 that the transition of sand into mud is veiy abrupt, particularly near the western shore. Here, two small beaches lie almost completely sheltered behind two headlands and there is consequently almost no water movement. As a result, mud settles very close to the low-water line. Sample 137 was taken in water only 75 cm deeper than sample 138, but their means are +7.59 and +2.21 phi, respectively. The transition is almost equally sharp at the opposite shore. The small band of sandy mud contains more than 85% mud (Fig. 10B), and mud is deposited into the very mouth of the Beluso River. In all probability the river only brings in fine and coarse silt during times of heavy rainfall, and normally transports only clay. This is reflected in the grain-size distributions of the muds: samples 131, 139, 141, 256, 692, and 897 (eastern part) show a weak mode around +5 phi; all the other samples (western part) show a concentration in the clay fraction only. The first six samples therefore have lower skewness values and are slightly more poorly sorted (Fig. 10, A & C). The Beluso River probably never supplies sandy particles to the Ria de Abanqueiro; petrological confirmation of this conclusion is given on page 114.

Ulla River

In the upstream part of the Ulla River (inset Fig. 4) the water follows a channel one to several metres deep between several islets; in the estuary the course of the river is divided among numerous channels between submerged banks. Samples were generally taken from the bed of the stream. All sands and coarser sediments display unimodal frequency distributions; the five samples containing more than 10% mud, however, are bimodal or polymodal (Fig. 11A). The grain-size gradually decreases downstream, but is everywhere much too coarse with respect to the low current-velocity (see page 81). In all probability the greatest part of the present-day cover of the streambed was determined by climatic conditions with more water discharge, i.e. it must date from glacial times. Fine sand has accumulated since the inundation of the ria directly at the mouth of the river. A Dachnowski boring-profile at station 755 yielded 8½ m of almost uniform muddy sand.
Rivers with comparable aspects can be found at many places, for example the Loire in France. Berthois (1955) differentiated the Loire sediments into six types: (1) high sand-banks with very poorly sorted pebbly sands, (2) shoals with poorly sorted coarse to very coarse sands, (3) streambed with relatively strong current velocities and moderately well-sorted coarse sands, (4) bimodal sediment after a period of high-water with very poorly sorted coarse sand mixed with well-sorted fine sand, (5) polymodal reworked sediment of extremely poorly sorted material, and (6) moderately to well-sorted fine sands in the estuary.
Since the very coarse and pebbly sands of the upstream part of the Ulla River have means between —1 and +1 phi and are moderately sorted (Fig. 11A), they fall between Loire types 2 and 3. This may indicate that during glacial times current velocities were slightly higher in the Ulla River than in the Loire River. The finer tail of the grain-size distribution may have



been partially reduced: the skewness value is in general weakly positive and sometimes even negative. Two samples do not belong to this type, viz. the coarse mixtum of station 913 and the muddy coarse sand of station 915. These samples were both taken very close to a sand bank and show the granular properties of Loire types 4 and 5.

The estuarine samples and those taken in the mouth of the Ulla River show wide variation in skewness, and the finest sediments (e.g. 143, 250, 755, 838) are not the best sorted. The similarity to Loire type 6 is not great. This estuary is very wide and the submerged banks are only slightly shallower than the gullies, so only extremely low current velocities can occur here. Redistribution of sand particles can only take place on a small scale here during times of heavy rainfall, thus locally reducing the value of the standard deviation. The poorest sorting is shown by samples 146 and 253, in which the addition of coarse beach sand results in polymodal grain-size distributions.

We may conclude that this sediment, both in the upstream part of the river and in the estuary, is not in accordance with the present transport capacity of the Ulla River (cf. Griffiths 1951, Wood 1964). Transport of sandy particles into the ria can only take place incidentally, as will be further discussed on page 113. This transport must be confined to very fine sand; Cadée (1968, p. 32) mentions that freshwater mollusc shells do not occur in the ria outside the mouth of the Ulla River.

NW coast of the ria

The grain-size data of samples from the Ensenada de la Merced have been plotted in Fig. 12 (dots). Sands derived from local weathering profiles are found only in the immediate vicinity of three small rivers. The rivers themselves, however, bring in only mud and even that in small quantities. Other possible mud-supplying sources (such as the Ulla River) are far away, and consequently the rate of sedimentation in this bay may be far lower than in the Ria de Abanqueiro. Sands lie everywhere along the coast but extend locally to different water depths.

Tidal currents pass by outside the bay. The entrance of the Ensenada de la Merced is very wide, however, and when waves are occasionally generated on the ria they have free access to the bay. Such waves would prevent the deposition of much mud in shallow waters in most places. Although a muddy fraction is already present near the low-water line (Fig. 12B, stations 81 and 926 at 2½ and 4 m water depth, respectively), pure muds are first met with at depths of over 10 metres.

Submerged bare rocks are found along the eastern and western coasts of the inner part of the bay. Along the beach in the north they are also numerous but are covered by a thin layer of sediment; a Dachnowski boring at station 926 yielded 50 cm sand, separated

Fig. 10. Grain-size parameters of non-calcareous fractions; Ria de Abanqueiro (in C: 245 should read 254).

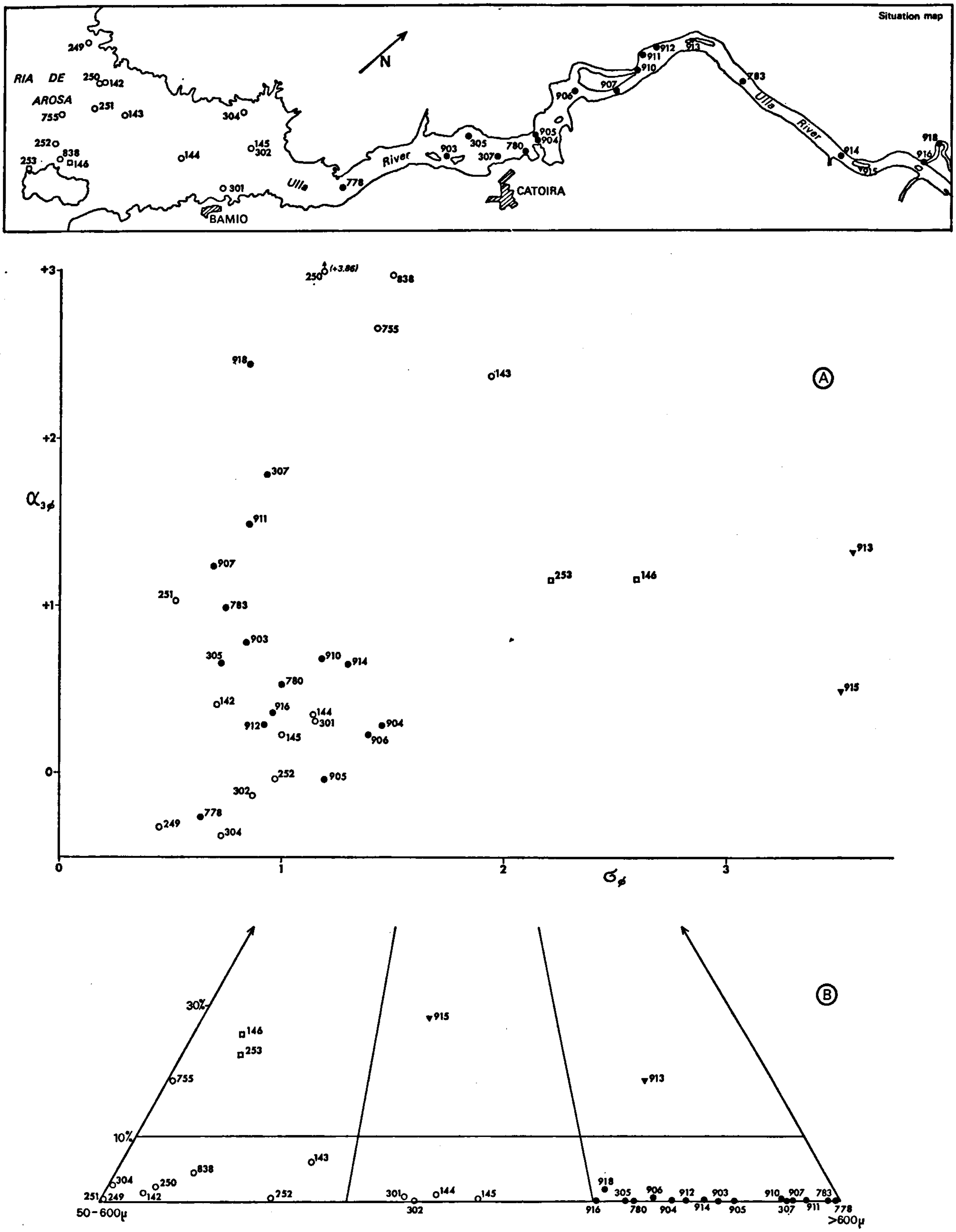


Fig. 11. Grain-size parameters of non-calcareous fractions; Ulla River.

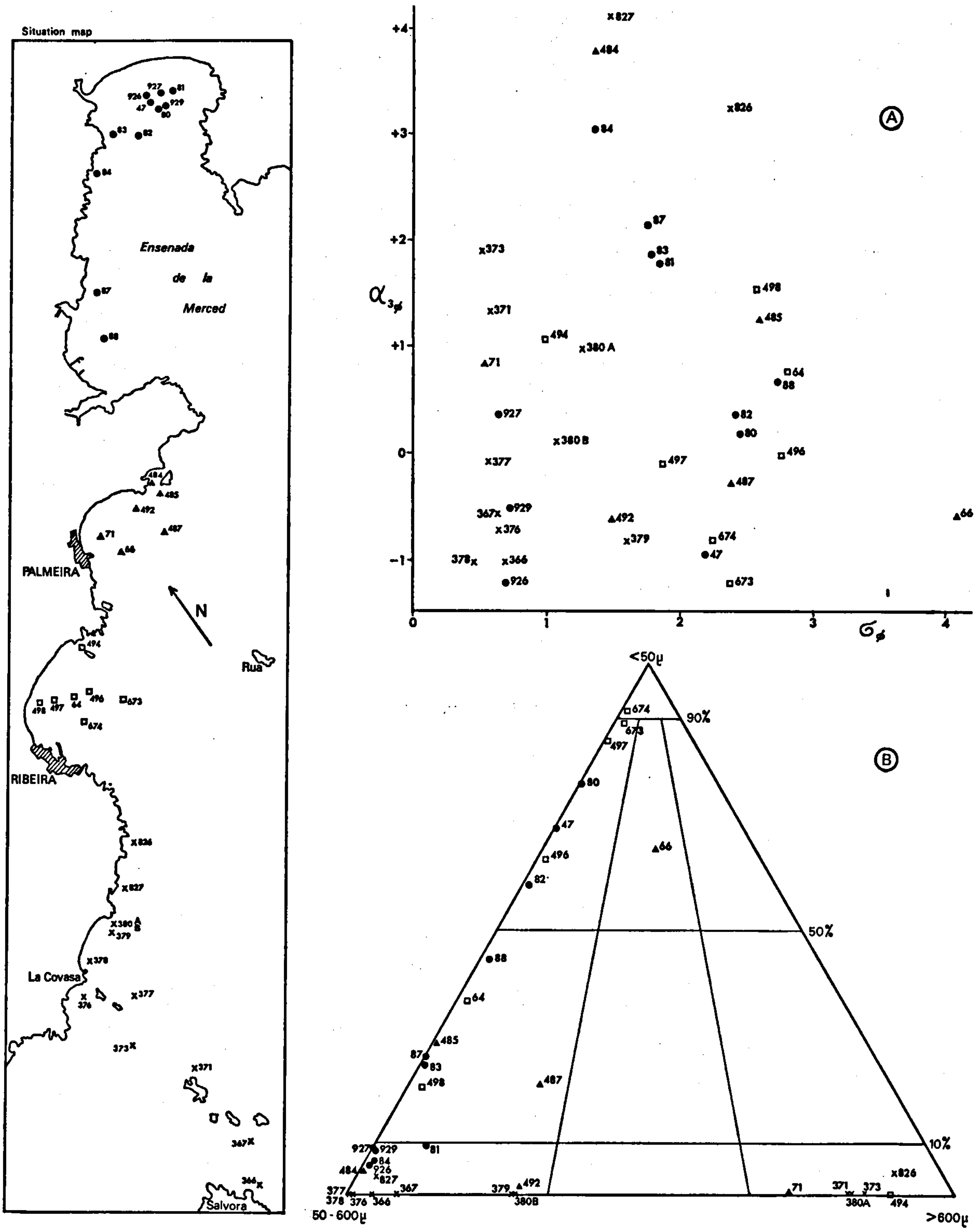


Fig. 12. Grain-size parameters of non-calcareous fractions; NW coast.

from the hard rock by a thin layer of fine-grained shell debris. A similar sequence was obtained at station 927; hard rock was already encountered under 20 cm of sediment at station 929.

It will be clear that the local topography plays a dominant role in the sedimentation pattern in such a quiet environment (Wood 1964), resulting in widely varying values of sorting and skewness. The sign of the skewness is mostly positive, which is normal for marine sediments in such a quiet bay (cf. Duane 1964). Sample 929, taken at a depth of 8 m, nevertheless contains so little mud that it looks like a normal — negatively skewed — moderately well-sorted beach sand.

Samples 47, 80, 82, and 88 are very to extremely poorly sorted; the frequency distributions are bimodal, i.e. they display modes in the fine sand class and in the clay or finest silt class. Arps & Kluyver (1968) found bimodality in beach sands (devoid of mud), but there the second mode often lay in the pebbly sand class as a result of its origin from two types of granite. Grains coarser than —1 phi do not occur in the marine sediments investigated in the present area. The bottom configuration in the waters opposite Palmeira is very rough, and the individual samples (triangles) show widely differing characteristics (cf. Figs. 4 and 12). The very coarse sand at station 71 and the sand at station 484 are unimodal, and the other shallow sample (492) has a faint second mode in the very coarse sand class. The three other samples have polymodal distributions and therefore high values of standard deviation. The combination of several local factors — water depth, situation of the station with respect to isolated rocks, the type of the local bioclast — exclude a general trend; the term 'micro-environment' could be applied to each individual sample.

Bare rocks are absent in the western part of the bay before Ribeira, and here there is a better relation between the coarseness of the sediment and the depth of the water (see Fig. 12B; open squares). Sample 497, taken at the same water depth (18 m) as sample 673, is situated on the map between stations 498 and 64, indicating that at this spot there is a depression which is not shown on the nautical chart and whose origin is not understood. Sample 494 is a unimodal pebbly sand; the finest sandy mud (673) and the mud (674) are also unimodal. The frequency distributions of the other samples with intermediate means and water depths show one or two rather weak modes; their plots lie in the same area in Fig. 12B as the bimodal sandy muds and muddy sands from the Ensenada de la Merced.

The last series of samples plotted in Fig. 12 (crosses) are situated along the coast NE of La Covasa and around the island-arc towards the Isla de Salvora. The northernmost samples 826 and 827, a pebbly sand and a sand respectively, were taken at a water depth of 4 m along a coast with poorly developed beaches. These samples are poorly sorted due to the presence of a small quantity of coarse grains, but the distributions are still unimodal. The high positive value of the skewness points to an aeolian origin of the bulk of the material (Duane 1964); dunes are indeed present on the nearby mainland.

Samples 380A (about 2 m seawards from 380B) and 373 have been included with the ones already treated on page 96 in relation to the bioclastic fraction. The sediment at stations 379, 380A, and 380B show their twofold origin (aeolian and beach-derived) by bimodal frequency distributions; the other samples are all unimodal and well to moderately well sorted. It is noteworthy that all sands from the island-arc were collected in shallow water less than 10 m deep, but the very coarse sands (371, 373) at water depths of 14 m.

The area south of El Vado

Grain-size parameters of samples from the Umia River and from the area before its mouth and south of El Vado are shown in Fig. 13. The sediment from the streambed of the river is hardly consistent with this environment of a sluggish river. The mean grain-size does not gradually decrease in the downstream direction. Samples 950 and 966 are gravels, and hence are not plotted in the graphs; the other four are pebbly sands. The three southernmost samples from the delta fall in the same area (very coarse sands) in the triangular diagram. A comparison of old aerial photographs with the situation today led the present author to deduce a shift of the river mouth to the right, in a northerly direction. The seven samples mentioned so far indeed display similar environmental characteristics, namely those of relict coarse-grained river deposits.

The frequency distributions are unimodal although meso- to platykurtic, and are accordingly moderately to poorly sorted, with positive skewness. The river certainly carries mud (and occasionally perhaps even very fine sand), but this component is not found in the streambed. During high-water tide the river overflows its low banks and the whole area outlined on the situation map is drowned under very slow-streaming water (salt water penetrates up to station 943 under normal weather conditions); brackish marshes have developed on either side of the actual streambed. At low-water tide, however, the river flows more rapidly through a narrow channel and carries suspended fine sedimentary particles into the ria. The moderately sorted sands and coarse sands of the delta also contain less than 1% mud. Only sample 958 was taken from the streambed; all the other stations lie on the delta, which is almost dry most of the time.

The sediment of the area between El Vado and El Grove has been described by Nonn (1966, p. 328) as a mixture of sandy clay with coarse-grained quartz and gravel. Mixtures of that nature would lead to bimodal fine and coarse mixtums or at least to muddy coarse sands, but such textural compositions do not occur in this area (Fig. 13B). Only some plots of the total sediments fall in these fields (see Fig. 9). Nevertheless, almost all the samples do show bimodality; this is hardly visible in the coarser sediments, but the muddy sands have a distinct second mode in the clay fraction and the sandy muds have a fine sand mode (only sample 735, taken at 18 m water depth, is unimodal). Accordingly, the second and third moment of their grain-size distributions have no environmental significance, but they have been plotted in Fig. 13 to make the descriptions complete.

From a comparison of the two parts of Fig. 13, the influence of the textural composition on the statistical parameters can be inferred. The sands and coarse sands in the shallowest waters have less than 1% mud, have unimodal and almost symmetrical frequency distributions, and are moderately sorted. An intermediate mud content (up to about 30%) results in a high standard deviation and a quite distinct skewness. The finer sediments contain more mud but sand grains are still present, i.e. the frequency curve becomes flatter and more symmetrical, so that skewness decreases again and the degree of sorting has now become extremely poor.

We have provisionally assumed (page 97) that this area represents a relict sediment similar to that in the ocean where samples 814 and 815 were taken, but the origin of the sediments in this region is obscure. Nonn (*ibid.*) supposed that the components originated from continental kaolinitic mud and Flandrian material from the estuary of the Umia River. We shall see below (page 113) that this area and the Umia River are petrographically different and form two distinctly separate heavy-mineral associations.

The detection of bimodality

Since the renewed interest in moment measures for the differentiation of sedimentary environments initiated by Friedman (1961), these parameters have mainly been used by investigators of fluvial sands and deposits from the coastal area, especially beach and dune sands. With this method, the environments of both recent deposits (Duane 1964, Sevon 1966, and others) and Pleistocene deposits (Schock 1965) have been successively distinguished.

In the present study moment measures have been employed to describe marine sediments, mainly those below wave base. An attempt has been made to deduce environmental properties from these measures despite the fact that many of the granular distributions were bimodal or even polymodal. Although local

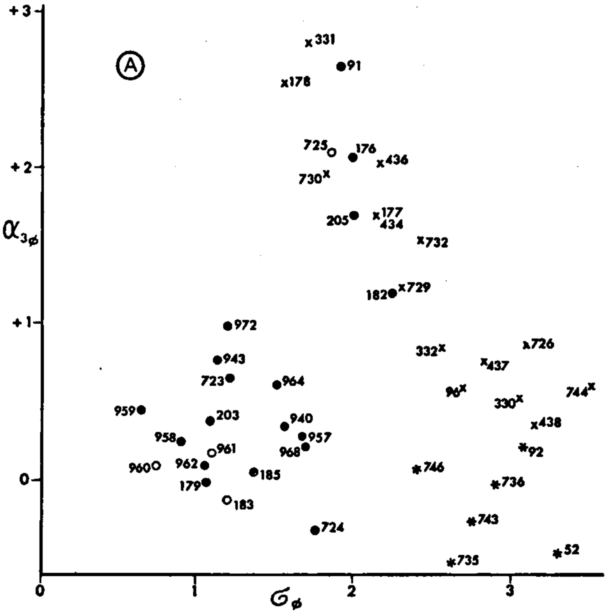
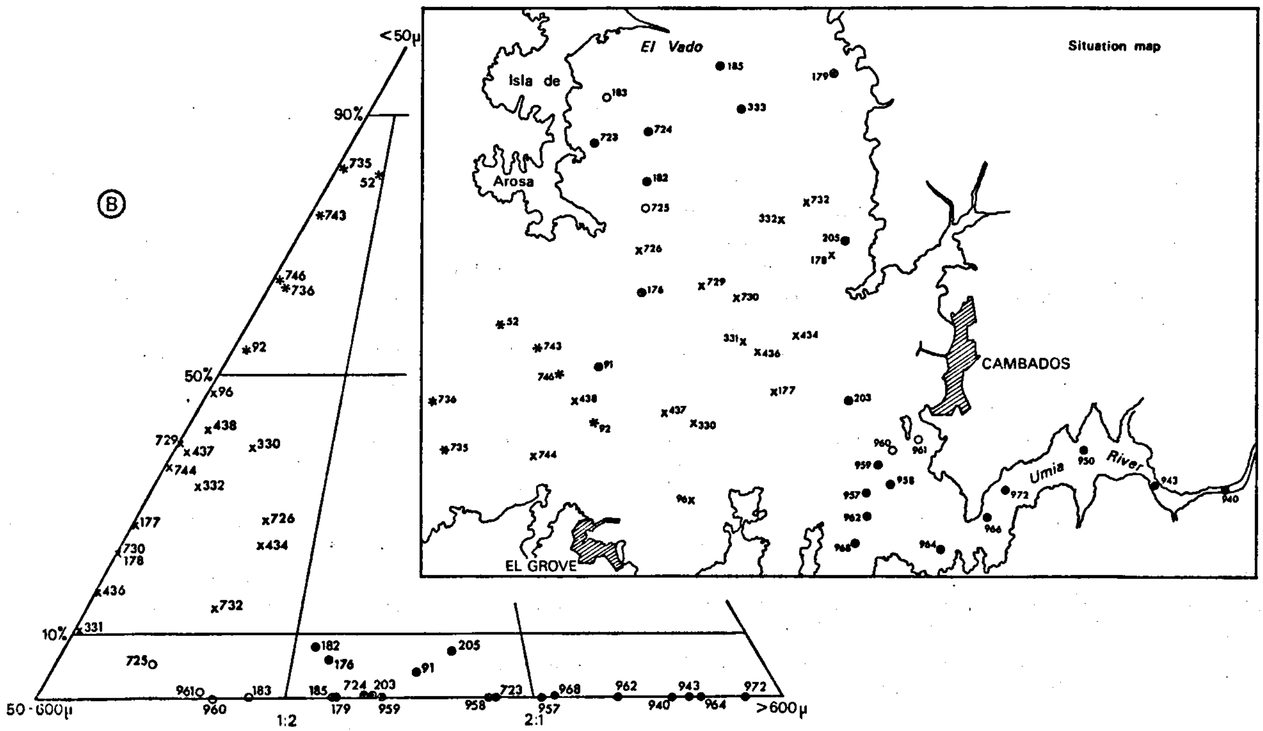


Fig. 13. Grain-size parameters of non-calcareous fractions; S of El Vado.



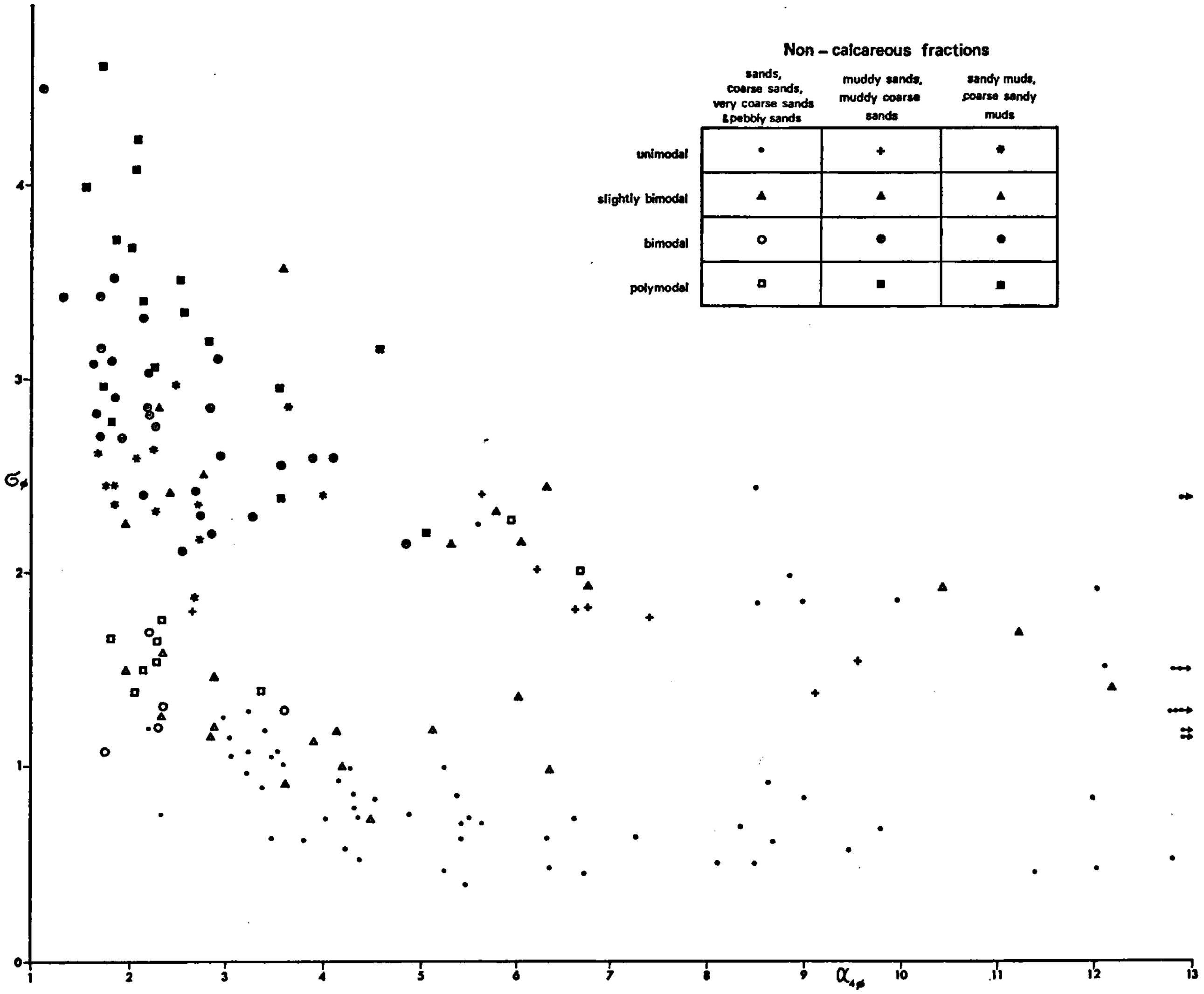


Fig. 14. Frequency modes of non-calcareous fractions (standard deviation versus kurtosis).

peculiarities could be explained in this way, a general trend in parameter values for the marine sediments of the ria as a whole could not be found. Such rather unsatisfactory results, caused by intricate topographical features, have also been found in similar environments, for example Saginaw Bay in Michigan (Wood 1964). Kurtosis, the fourth moment defining the peakedness of the grain-size distribution, has occasionally been mentioned in our granulometric descriptions. According to Friedman (1961, 1967), the environmental significance of this measure is not apparent in most cases; the range of kurtosis values for some selected beach and river sands in the Ria de Arosa is similar (Koldijk 1968). However, kurtosis might be useful as a means to detect bimodality. If, for example, the parameters of a distribution show symmetry and very good sorting, the value of the kurtosis may differ greatly from 3 (= lognormality); this will be particularly the case in bimodal distributions (McCammon 1962).

The spread of the grains over the size fractions is best expressed in terms of the even moments. The standard deviation has been plotted against the kurtosis in Fig. 14 for all non-calcareous fractions excluding the muds. This graph demonstrates that the greatest part of all sandy sediments (less than 10% mud) in the ria are moderately or moderately well sorted. Poorly sorted distributions are rare. More than 10% mud results in very to extremely poor sorting values, and the scatter of the plots shows that there is no relation between the standard deviation and mud content of these ria sediments.

Bi- and polymodal sediments are concentrated at the extreme left of Fig. 14, i.e. they show platykurtic or mesokurtic grain-size distributions. With only a few exceptions, non-unimodally distributed samples with less than 10% mud are poorly sorted. Among the muddy sands and muddy coarse sands there are just a few unimodal distributions, all of which are leptokurtic and also less poorly sorted than the polymodal ones. The same relative position in the diagram is found for the sandy muds and for the coarse sandy muds; the unimodal plots all concern samples with more than 75% mud. It has already been mentioned (page 88) that the muds of the Ria de Arosa generally contain almost equal amounts of clay and silt; although unimodal, the spread of all grains over five fractions evidently results in platykurtic frequency distributions of the muds.

Fig. 14 represents only a tentative attempt to detect bimodality. Half-phi sieves were employed in the present study, and the silt and clay fractions have even wider limits (Table I); reliable detection of bimodality requires the use of quarter-phi sieves (Middleton 1962), which will probably lead to better results in future studies.

ROUNDNESS

In addition to quartz and micas, the granites supply large quantities of feldspars — mainly potash feldspars. Roundness estimations of sand grains are, however, always done on quartz. The reason why feldspars are not rounded will therefore be briefly discussed in advance of the main treatment of roundness.

Thoroughly weathered granite generally produces angular quartz and feldspar grains (McEwen *et al.* 1959) without conspicuous difference in degree of roundness. Quartz and feldspar are equally resistant to mechanical forces, so the effect of differences in abrasion and attrition should be relatively insignificant (Kuenen 1959, Moore 1963). Chemical destruction of feldspar, however, takes place much more rapidly than that of quartz. This process is particularly active where sand is exposed alternately to water and air. Consequently, the feldspar grains encountered in our beach sands do not show any increase in roundness as compared to those in the weathering profile.

The roundness of quartz was estimated visually with a binocular microscope. The grain-size fraction of 1000 to 500 microns was divided into four equal parts; 25 clear quartz grains of each of the four parts were compared with drawings from Pettijohn (1957, pp. 58—59) and classified according to his criteria. In this way, the distribution of 100 grains over five roundness classes was obtained. The mean value and standard deviation of this distribution were calculated after conversion of the class boundaries to an arithmetic scale. The arithmetic mean represents the roundness degree rho (from 0 to 100, the latter for perfect spheres). The standard deviation is 0 when 100 grains fall in one class, and is 1 when each class contains 20 grains. The results have been plotted in Fig. 15.

Experiments by Kuenen (1959) have shown that rho increases rapidly with grain-size. The 1000 to 500 micron fraction (0 to +1 phi) covers a large grain-size range, but Table 3 shows that the variation in roundness values is not granular, i.e. the variation does not result from differences in the grain-size distribution. The three values for the weight percentages represent the three grain-size fractions from which the quartz particles were taken for roundness estimation. These fractions were recalculated to a total of 100%. It can be seen from this Table that rho is independent of the mean grain-size and that widely divergent rho values have been found for samples with nearly the same size distribution in the range from 1190 to 420 microns (approximately from —¼ to + 1¼ phi).

In the Ulla River and the inner part of the ria, the rho values are less than 20 and the standard deviation is relatively low (± 0.35). Angular and subangular grains can thus be considered as having originated from the metamorphic rocks of the Ulla drainage basins.

The largest rho number, however, was also found here, i.e. 52 for station 869. All the mineral constituents of station 869 show a high degree of roundness; almost all garnet and staurolite grains, for instance, are well rounded. This sample is exceptional here, because at the nearby stations both rho and standard deviation are low. The only possible explanation is found in the local degradation of a small old beach deposit on the neighbouring islet, which is the more probable because the mainly metamorphic heavy mineral composition is not in accordance with the granitic rocks on the island (cf. page 112).

Along the northern coast of the ria, both rho and standard deviation increase slightly in the direction of the ocean. We may assume that the beach sands show the same tendency. Saínz-Amor (1960) also observed a slow increase in roundness (from Pettijohn's class B to C) in the Ria de Vigo in the direction of the ocean. He concluded that there is no marked influence of marine transportation.

Another process, however, may also have had an in-

TABLE 3. The relationship between roundness and mean grain-size.

station no.	$\bar{x}$	weight percentages from grain-size distr.; (fractions in μ)			recalculated to 100%			rho
		1190 850	850 600	600 420				
394	365	5.7	12.0	18.2	16	33	51	15
195	15	0.2	0.8	1.7	8	29	63	22
352	530	8.7	21.5	30.5	14	35	51	28
772	350	7.8	20.8	29.8	13	36	51	44
869	4.3	0.1	0.3	0.5	11	33	56	52

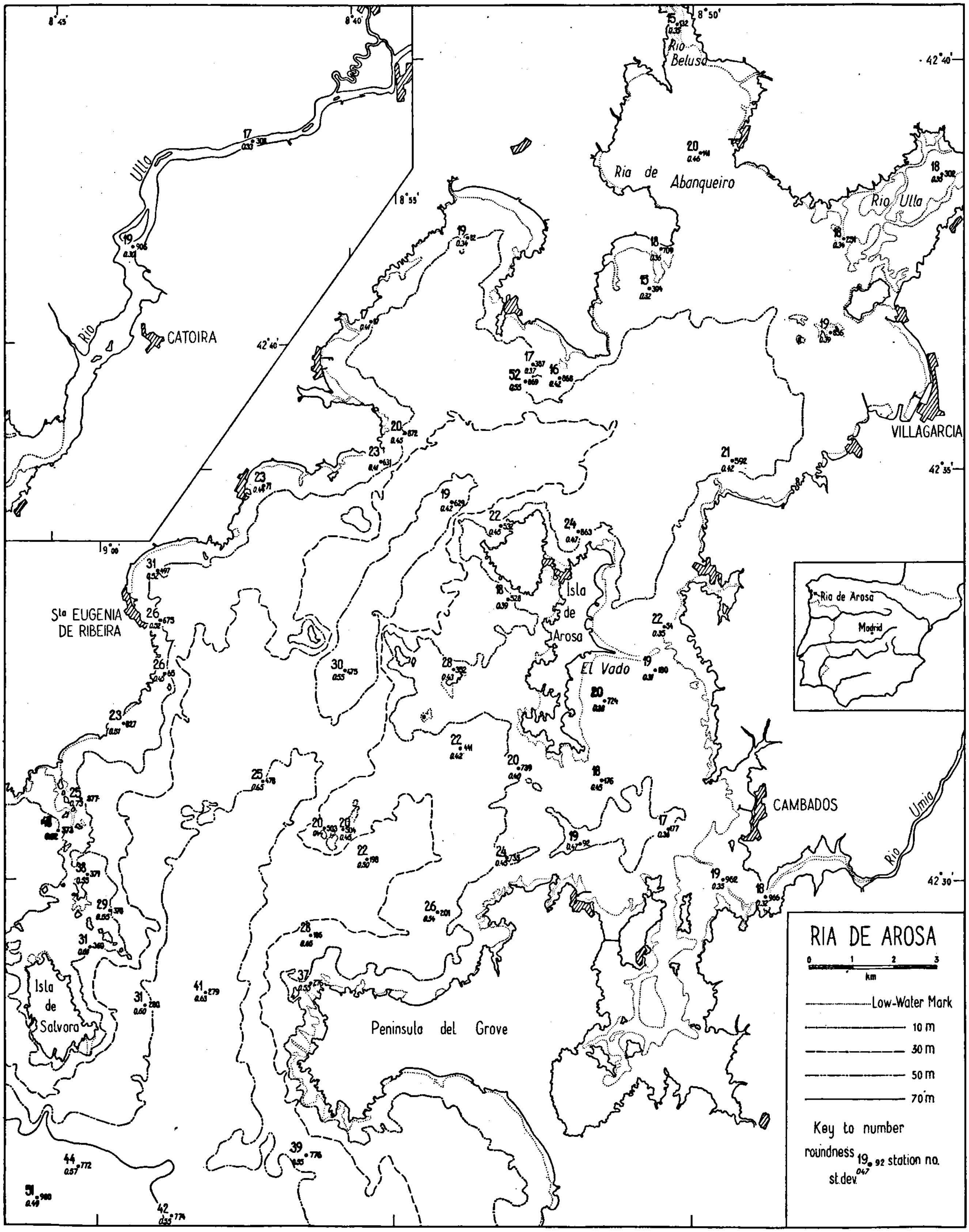


Fig. 15. Roundness of quartz grains at 57 locations in the Ria de Arosa (360 should read 367).

fluence. A detailed account of quartz grain-shapes has recently been published by Moss (1966). Moss and several other authors have mentioned that large quartz grains, in particular those from granitic weathering profiles, can sometimes be crushed between the fingers. These quartzes do not, however, break along conchoidal fractures but rather along more or less rectangular fractures that arose during cooling when, at a certain temperature and confining pressure range, quartz was more brittle than feldspar. This process results not in flinty fragments but in rather equant grains which by wear acquire a relatively high sphericity. The sphericity of most quartzes of the ria sands is indeed rather high.

The fraction of 1000 to 500 microns may be the smallest particle size produced by this process in the Barbanza granite. Quartzes of this grain-size rarely disintegrate into still smaller grains (cf. page 116). The surface of these granite-derived quartzes are probably not smooth, due to the presence of numerous small defects representing continuations of the rectangular fractures mentioned above; accordingly, this surface may be relatively sensitive to attrition as compared to metamorphic quartzes. The slow increase in roundness toward the ocean could be a result of an increasing ratio of granitic quartz to metamorphic quartz. That we find subangular roundness values in the area Umia — El Grove — El Vado need not be taken as contradictory to the pracess outlined avobe, because the rocks on this side of the ria are mainly composed of a different, intrusive granite (Caldas de Reyes type).

The values for the group of islands from the Isla de Salvora to La Covasa plainly show the mixing of the subangular to subrounded local ria sands with the almost well-rounded sands of the Atlantic Ocean. The highest standard deviations are found here (± 0.60). Further out in the ocean (stations 772 to 900) the decreasing influence of the ria sands is demonstrated by a moderate rise of rho accompanied by a decreasing standard deviation. Rounded to well-rounded sands were also found on the Islas Cies opposite the Ria de Vigo (Saínz-Amor 1960).

The coarser constituents of the ocean samples are well-rounded. The decalcified sample 772 (water depth 80 m) contains 4% very well-rounded gravel, with sizes mainly between 5 and 10 mm. The mouth of the Ulla River and its accompanying ocean beaches must have been located in this region during the last cold phase of the Pleistocene. Since then, the beach gravel must have been spread over a greater area.

HEAVY MINERALS

Total heavy-mineral content

Table III lists the heavy-mineral contents of 52 samples (for positions of the stations, see Plate 2). The third column ($\bar{x}$) gives the arithmetic means of the entire grain-size distribution of the non-calcareous fraction in microns (-u- = mean unknown, sample with high carbonate content). The heavy-mineral percentages apply to the 500 to 50 micron fraction from which the slides were made, as is usual in heavy-mineral studies. Grains coarser than 500 microns only occur occasionally and the omission of this fraction would not seriously affect the percentage values, but the unknown amount of heavy minerals smaller than 50 microns might give a higher percentage for the entire sample. On the whole, the percentages are low. Nevertheless, the separation of the heavy minerals proved useful, even for the finest sediments; the general statement of Van Andel (1959) that a heavy-mineral study of silty clays (muds) and shales is unrewarding does not apply to the recent muds of the Ria de Arosa. Station 590, for example, has a mean $\bar{x}$ = 3.1 microns and the weight of the 500 to 50 micron fraction is only 1.5% of the entire non-calcareous fraction. However, 15 different kinds of heavy minerals were found, even though the heavy-mineral percentage is only 0.1%.

Seeking a relationship between mean grain-size and heavy-mineral content, Poole (1958) studied two bays in Texas (USA). In Mesquite Bay, which displays a simple sediment pattern, the heavy-mineral percentages of the sands clearly showed a parallel trend with increase of the grain-size of the sediments. In the adjoining San Antonio Bay, however, no similar relation was found. Poole ascribed this discrepancy to the great variety of sediment-types arising from the complex bottom topography of this bay. The same applies to the Ria de Arosa, as is shown by the data in Table III.

A second factor of particular importance in determining the heavy-mineral content of fine sediments is the grain-size of certain of the heavy minerals themselves. The presence of zircon, for instance, may strongly influence the total amount of heavies (cf. stations 588 and 590). According to Brajnikof (1944), the granular mode of zircon is 45 microns.

Other heavy minerals have different typical grain-sizes, but it is difficult to determine the combined influence on each individual sample. The fractional percentages in Table IV show a distinct concentration of the heavy minerals in the 75 to 50 micron grain-size fraction for six samples lying within the ria, but a concentration maximum in the 150 to 75 micron fraction for the other stations (776, 815, and 900), which are situated in the ocean.

Heavy-mineral counts

Line-counting was carried out to obtain an estimation of the relative frequencies of the heavy minerals. This method takes the least time but is rather dependant on specific particle-size. Line counts from slides of known numerical composition carried out by Van Harten (1965) resulted in number percentages too high for coarse grains and too low for fine grains. According to Van Harten, ribbon-counting should be applied to reduce the influence of this preferential particle-size of certain heavy minerals.

However, fine mineral particles usually require inspection of interference figures for proper identification, which involves frequent shifting of the slide. If the slide is not accurately returned to the original

position within the chosen ribbon boundaries, an error will be introduced. Furthermore, so many fine-grained samples were involved that ribbon-counting would have been too time-consuming in the present study. Line-counting therefore seemed preferable. A considerable number of samples were subjected to fractional analyses in an attempt to discern the influence of the grain-sizes of the various minerals on the heavy-mineral composition (granular variation).
Differences in heavy-mineral assemblages can also be caused by chance variations. These arise mainly from sampling errors, irregularities in laboratory treatment, and uneven distribution of the grains on the slide (Doeglas 1940). Variations due to the last of these can be diminished by increasing the number of counts. Blankenburg & Jagusch (1964) have provided a Table for a confidence range of 95%. If a given mineral comprises 20% of all heavy minerals, the range is ± 8.0% for a total count of 100 grains, ± 5.6% for 200, ± 4.6% for 300, and ±2.5% for a count of 1000 grains. This single example shows that the range for 100 grains is quite large but that counts of more than 200 are virtually not worth the time involved. The confidence range of epidote percentages calculated by Poole (1958) fits well with the values in Blankenburg & Jagusch's Table 7.
The counting procedure used in the present study was as follows: 200 grains were counted and the percentage of opaque minerals recorded. After recounting to 200 with omission of the opaques, the alterites (for definition, see page 109) were noted as a percentage of the non-opaque heavy minerals; a second recount to 200 gave the relative percentages for the non-altered non-opaque heavy minerals. This procedure proved applicable to 258 of a total of 317 slides. The counts of 14 slides containing 151 to 199 grains of non-altered non-opaque minerals, 12 slides with 101 to 150 grains, and 13 slides with 51 to 100 grains, were converted to 100%. Twenty slides carrying fewer than 51 grains were discarded as having 'insufficient heavy minerals'.

Heavy-mineral identification

The heavy-mineral slides were examined under the monocular polarizing microscope, and the observations were compared with the descriptions in Tröger (1959) and Milner (1962b). The species encountered were identified on the basis of the characteristics mentioned below. The minerals are listed in alphabetical order, the more important ones being capitalized.

Anatase. Euhedral, usually square. Clear grains. Generally faintly bluish; occasionally colourless, or bright yellow. Nearly isotropic, distinct interference figure. Grain-size 150 to 50 microns.

ANDALUSITE. Irregular shape, rounded corners. Abundant random black inclusions; chiastolite only found once. Strong pleochroism from a strong pink to very pale green, or colourless. Length-fast. All grain-sizes; slight preference for coarse grains.

Brookite. Irregular shape; rarely prismatic. Clear or turbid brownish. Very bright interference colours, mainly green and purple. Distinct interference figure with strong axial dispersion. Grain-size 150 to 50 microns.

Chloritoid. Irregular shape. Turbid; inclusions. Faintly pleochroic from greenish to bluish. Interference colour grey. Distinct interference figure. Grain-size 300 to 50 microns; preference for small grains.

Corundum. Rhombohedral or irregular angular shape. Clear grains with very high relief. Colourless or faintly bluish. Grain-size only 75 to 50 microns: identification doubtful.

EPIDOTE. This group-name is used in the following sections for the pistacite-clinozoisite series and zoisite. *Pistacite:* Mainly irregular, rounded shapes, often turbid. Sometimes euhedral clear grains composed of one or several short prisms. Typical yellowish-green colour of variable intensity, which also dominates over the interference colours. Generally weakly pleochroic. All grain-sizes. *Clinozoisite:* Irregular or rounded shape. Clear or turbid grains. Interference colour bluish-grey. Biaxial positive with large axial angle (cf. zoisite). All grain-sizes; preference for small grains. *Zoisite:* Irregular shape. Generally rather turbid. Interference colour bluish-grey; often anomalous blue. Biaxial positive with small axial angle (cf. clinozoisite). All sizes; preference for small grains.

GARNET. Isotropic. (a) Angular shape. Clear, rarely with inclusions. Colourless or faintly pink. (b) Angular to subrounded. Sometimes clear, but generally showing abundant black inclusions. Faint to strong pink. (c) Angular to subrounded shape. Clear grains. Yellowish to yellowish-brown. Garnets occur in all grain-sizes; only variety (c) shows a preference for coarse grains.

HORNBLENDE. Group consisting of several varieties. (a) Short prisms with cockscomb ends. Generally clear grains, often with a sprinkling of small inclusions. Distinct cleavage parallel to the length. Medium green, less frequently brownish; pleochroic in different tones. Intensively coloured specimens show a fresh appearance; light to nearly colourless ones may seem turbid due to alteration. (Hornblende is gradually deprived of its iron content in the transitional weathering zone, resulting in discoloured and turbid hornblendes (Bisdom 1967b) and in the formation of limonite and goethite (Bisdom 1967a). Predominantly green (second order) interference colours. These specimens are referred to as 'normal hornblende' in the following sections, although some of them may be cummingtonite (Arps & Kluyver 1968). No preferential grain-size. (b) Same shape as (a). Very dark green to nearly opaque, with only the rims faintly green and translucent. Referred to as 'dark hornblende'. All grain-sizes, slight preference for 300 to 75 microns. (c) Same form as (a). Pleochroic from yellowish-brown to reddish-brown. 'Titanhornblende(?)'. Grain-size 75 to 50 microns. (d) Elongated prisms with pointed ends. Clear with an occasional small inslusion. Very distinct cleavage. Colourless. Referred to as 'tremolite(?)'. Coarse grains.

Hypersthene. Very angular prisms, minutely dentated at the ends. Finely striated clear grains. Rounded grains also occur, with inclusions oriented parallel to the length. Very distinct cleavage. Strength of pleochroism variable, from bluish-green to a strong pink. Bright interference colours. Length-slow. Grain-size 300 to 75 microns.

KYANITE. Oblong prisms with rectangular outline, arising from very distinct basal cleavage. Clear grains, rarely with inclusions. Colourless. Other typical properties: extinction angle and distinct interference figure. Grain-size 300 to 50 microns.

Monazite. Rounded grains. Clear with very high relief. Faintly yellow. Identification doubtful. Most monazite could have been disintegrated during laboratory treatment, because it is soluble in acetic acid (cf. De Graaff & Woensdregt 1963).

Rutile. Elongated rounded shapes. Clear grains with very high relief and distinct cleavage parallel to the length. Pleochroic from yellowish-brown to reddish-brown; occasionally almost opaque. Extreme birefringence. Grain-size 300 to 50 microns; preference for small grains.

SILLIMANITE. *Grains:* Prisms with rectangular outline. Transverse fractures. Clear grains; isolated inclusions common. Colourless. Bright interference colours. Small grains are distinguished from kyanite by straight extinction. All grain-sizes; preference for small grains. Some coarse rock fragments occasionally present in the slides are referred to as 'sillimanite aggregates'; a large proportion of these aggregates is composed of sillimanite, the rest is alterite and either kyanite or staurolite. *Fibrolites:* Rounded irregular shapes, commonly with frayed ends. Inclusions. Colour dirty grey due to surface alteration. Composed of extremely fine bent fibres. All grain-sizes; preference for coarse grains.

SPHENE (= titanite). Subangular or rounded irregular grains. Clear grains, sometimes partly altered. Etched appearance, probably due to laboratory treatment. Pleochroic from light yellowish-brown to dark reddish-brown. Extreme birefringence. Occasionally, anomalous blue extinction. All grain-sizes; strong preference for coarse grains.

Spinel. Isotropic. Rounded shapes, sometimes octagonal. Clear grains. Green; very rarely faintly blue. Identified by X-ray diffraction photo. This mineral was most probably mistaken for uwarowite by Saínz-Amor (1959). Grain-size 300 to 50 microns.

STAUROLITE. Inregular forms, mostly rounded. Abundant black inclusions, otherwise clear. Pleochroic from light or orange yellow to yellow or reddish-brown. Predominantly greenish interference colours. All grain-sizes; slight preference for coarse grains.

Titanaugite. Irregular angular shapes, often rounded. Clear grains with dentated ends. Peculiar purplish-brown colour, faintly pleochroic. Strongly birefringent. Extinction angle˙ 45°. Sometimes clear interference figure. Grain-size 300 to 50 microns.

TOURMALINE. Occurs in several varieties. (a) Oblong prisms with straight, pointed, or irregular ends. Sometimes irregular outline; rarely zoned hexagonal basal sections. Clear grains, occasionally inclusions. Strongly pleochroic from yellow or light brown to dark brown; very rarely greenish-brown. Length-fast. Generally shows distinct interference figure. Referred to as 'normal tourmaline'. All grain-sizes. (b) Irregular shapes. Clear grains with inclusions. Faintly pleochroic from very dark brown to nearly opaque. According to Mrazek (1965), prolonged oxidation of tourmalines results in relative enrichment of dark-brown specimens. Referred to as 'dark tourmaline'. All sizes; preference for coarse grains. (c) Irregular shapes. Clear grains. Pleochroic from light to dark blue (indicolite). Distinct interference figure. Referred to as 'blue tourmaline'. All grain-sizes. Partially blue normal tourmalines of irregular and hexagonally-zoned shapes occur. (d) Same shape as (c), but pleochroic from pinkish-blue to deep purple. Briggs (1965) gave the name 'watermelon' to this peculiar pleochroic scheme. Here referred to as 'purple tourmaline'. All grain-sizes.

ZIRCON. Short or oblong prisms. Perfectly euhedral or subhedral crystals; subrounded grains less frequent. Clear grains with small inclusions. Colourless; only subrounded grains are sometimes faintly reddish-brown. Very strongly birefringent. Length-slow. Very strong preference for grain-sizes from 75 to 50 microns, but particles over 150 microns occur.

According to Van Andel (1950, p. 45), *alterites* are very fine-grained aggregates of unknown composition. If more than three-quarters of the grain is altered, Van Andel calls it alterite. In the present study heavy minerals undeterminable due to complete alteration were counted as alterites, thus including saussurite. The group of opaque minerals was not further investigated.

Provenance of heavy minerals

Several factors influence the heavy-mineral composition of a sediment and thus determine the assemblage encountered. Composition and weathering of the source rocks and mechanical and chemical attack during transportation and after deposition are the most important factors (Doeglas 1940).

For the possible origin of almost all the heavy minerals found in the bottom samples of the Ria de Arosa, the reader is referred to Floor (1968, Tables 1 and 2). A few additional remarks on the occurrence and abundance of some minerals will suffice here.

Bluish-green tourmaline (from mica schists) was not encountered, possibly because it had been chemically altered into more brownish types during weathering (Mrazek 1965). According to Von Raumer (1963), dark tourmaline derives from the Hercynian Barbanza

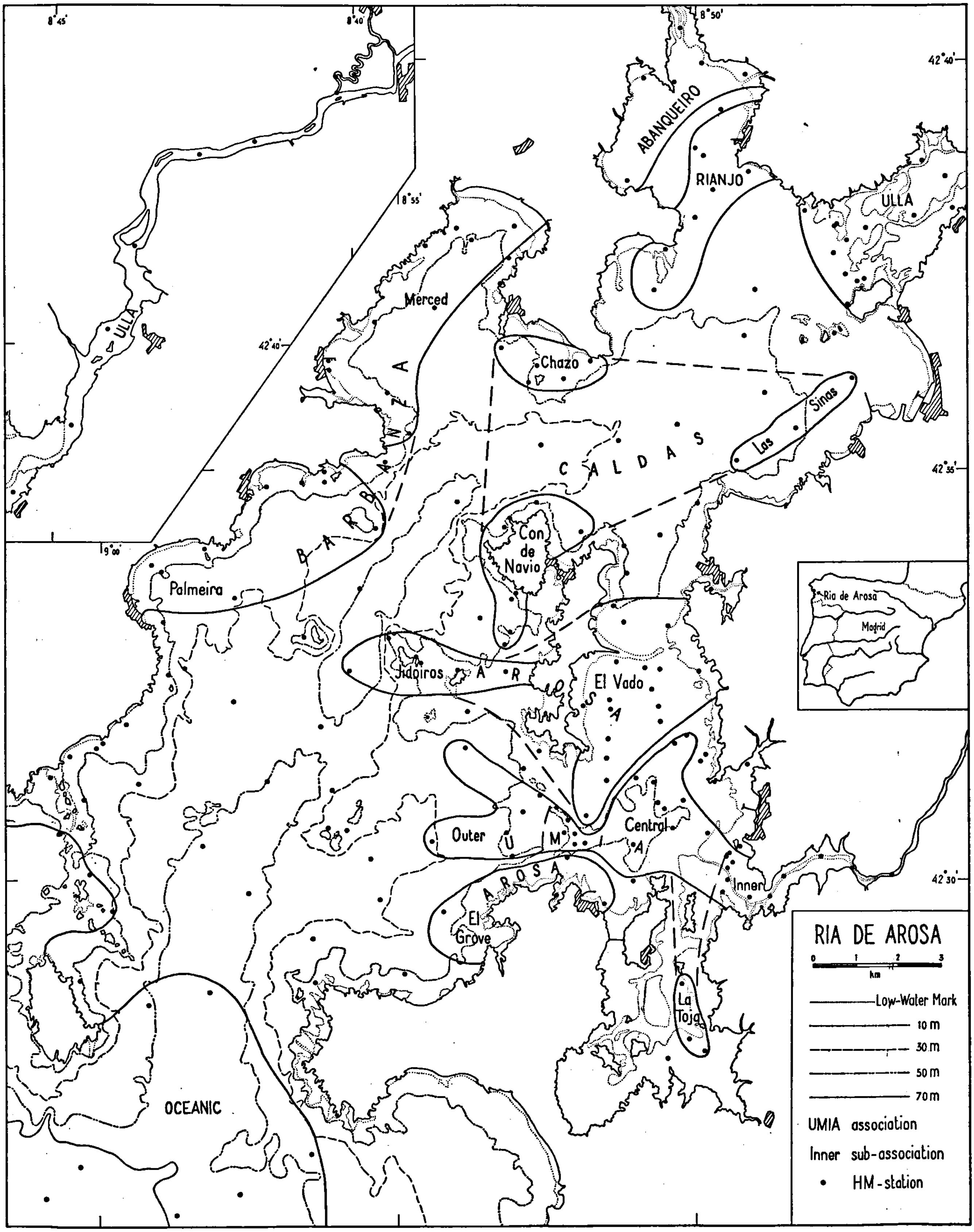


Fig. 16. Distributional areas of heavy-mineral associations.

granite in particular; when present, it forms only a part of the total tourmaline in the assemblage. Blue and purple tourmalines are always found together, both in very small amounts.

Only a small proportion of the zircons is subrounded. We may assume that these are of metamorphic origin (Saxena 1966, Kalsbeek & Zwart 1967) and that the granitic rocks mainly supply euhedral crystals (Arps & Kluyver 1968).

The types of garnet were not determined. Von Raumer (1963) mentions spessartite-almandite. According to Tröger (1959), the common pink garnets might be almandites and the yellowish-brown types spessartites. Arps & Kluyver (1968) also found yellowish-brown garnets in beach sands but not in the hinterland.

Brookite is not recorded in Floor's Tables. In the weathering profiles, however, it is found in small quantities together with anatase (Arps 1965). It can be assumed that anatase is already present in the parent rock and that it also forms authigenically together with brookite, titanium being provided by the weathering of biotite (Bisdom 1967b). Kaolinite has been reported to adsorb titanium (Stoch 1961). The fluviatile clays, which contain more kaolinite (and gibbsite) than those from the ria, have higher titanium contents (see Table V and page 120).

The abundance of staurolite and the presence of kyanite in many assemblages forms a problem (Arps & Kluyver 1968). Von Raumer (1963) did not report these minerals at all. Only xenoliths in the Barbanza granite might contain staurolite, but solely in accessory amounts (Arps 1965). Moreover, the chemical resistance of staurolite is low. In the hardness scale of Dryden & Dryden (1946) its relative number is 3, whereas the rarely encountered monazite, for example, ranks 40 (these numbers are based on a resistance of 100 for zircon).

For the possible formation of strongly pleochroic pistacites at the cost of biotite, see Floor (1968). Epidotes are easily destroyed. Therefore, euhedral pistacites can only be found in very recent deposits. They are provided by epidote-quartz dikes in the post-tectonic granites (Von Raumer 1963).

The Caldas de Reyes granite has a variable composition; one of the main types is a coarse-grained biotite-hornblende granite (Bisdom 1967b). The petrology of the region SE of the ria is not known in detail, but the hornblende content is thought to increase with greater distance from the supposed centre of the intrusion.

Von Raumer reported pyroxene from xenoliths in the Barbanza granite, and hypersthene could occur in basic rocks north of the Ria de Muros (De Graaff & Woensdregt 1963). Hypersthene is present in rare hornfels-xenoliths in the Caldas granite, according to Bisdom (pers. comm.). Enstatite, mentioned by Floor, does not appear in the above list. If present in the slides it has probably been mistaken for colourless hypersthene; the differential determination depends upon the opposite sign of the interference figure, which is indistinct in all our cases.

Heavy-mineral associations

The indiscriminate use of different terms to designate an areal unit characterized by a certain heavy-mineral composition has caused much confusion. Van Andel (1964), for example, in describing the heavy minerals of the Gulf of California, used the terms association, suite, and assemblage for the same distributional area of heavy minerals.

In this chapter the term assemblage is used to denote the heavy-mineral composition within one sample. A group of assemblages having approximately the same composition is called an association. A sediment-petrological province is made up of several associations. One such unit is the Ria de Arosa as a whole, since it is largely composed of sediments with uniform provenance, age, and regional distribution (Edelman & Doeglas 1933).

Plate 2 presents the heavy-mineral assemblages of the bottom samples in horizontal cumulative columns. The ten minerals capitalized in the list given above are depicted here separately except when they fall below 2%; the total of these minerals is always 95% or more. Twenty-nine samples (indicated in Plate 2 by an asterisk) were studied in four grain-size fractions; the results are shown in Plate 3. To facilitate comparison, the 'total' assemblage (500 to 50 microns) is depicted on both Plates. The complete lists of counts are not given, but these data will be supplied on request.

The wide variety of source rocks causes all assemblages to consist of a large number of mineral species (see Floor 1968). Nevertheless, eight heavy-mineral associations comprising nearly three-quarters of the investigated samples could be distinguished. The boundaries of these associations are shown in Fig. 16; to facilitate comparison with Plate 2, the stations have been repeated in this Figure.

The properties of the associations are as follows:

ULLA association. Percentage ranges: hornblende 17 to 50%, epidote 10 to 23%, tourmaline 2 to 7%, zircon 0 to 3%. Dark hornblende is present in all samples, but forms only a small fraction of the normal hornblendes. The epidotes are equally spread over all grain-sizes; there is slightly more turbid pistacite than clinozoisite. Dark tourmaline is seen occasionally, blue types are absent. The low percentage of zircon is not a result of the coarseness of the sediments, because it is also rare in fraction 4 (cf. stations 145 and 251, Plate 3); euhedral and subhedral or subrounded zircons are encountered in equal quantities. Yellowish-brown garnets are present in most of the slides. Staurolite is the most frequent of the metamorphic minerals, whereas chloritoid is absent. Sillimanite aggregates are found occasionally. Most upstream samples have more than 10% alterites, which is relatively high. Hypersthene is present in 12 of the total of 23 slides.

ABANQUEIRO association. Percentage ranges: tourmaline 27 to 82%, hornblende 1 to 33%, epidote 0 to 13%. Approximately one-fifth of the tourmalines are of the dark type; up to 2% blue tourmaline is found and purple tourmaline occurs occasionally. Dark hornblende is very rare or absent. Turbid pistacite is concentrated in the fine fractions; clinozoisite is rare and zoisite absent. Zircon is the dominant mineral in the 75 to 50 micron fraction; about one-third of the grains are subhedral or subrounded. Andalusite predominates in the metamorphic group; kyanite and chloritoid are absent. Spinel occurs in all but one sample. Only sample 132 contains titanaugite. Opaque minerals are concentrated in the fine fractions: e.g. 42% in fraction 4 of station 254.

RIANJO association. Percentage ranges: hornblende 25 to 85%, tourmaline 4 to 28%, epidote 1 to 23%, zircon 0 to 4%. All hornblendes are of the normal type, dark hornblende is absent; titanhornblende(?) was occasionally found. Dark tourmaline is generally present and forms about one-third of all the tourmalines in sample 394. Blue and purple tourmalines reach 1 to 2% for the three stations around Rubia, but are rare or absent in the samples from the other five stations. The ratio of pistacite to clinozoisite is 1; zoisite is rare. The low content of zircon is real (station 394, Plate 3), just as in the Ulla association; euhedral crystals predominate. Chloritoid was found for two stations only; all other metamorphic minerals are present throughout. Stations 709 and 394 show spinel. Alterites are rare or absent.

CALDAS association. Percentage ranges: epidote plus hornblende 54 to 71 %, tourmaline 1 to 6 %, garnet 1 to 5 %. Either epidote or hornblende is the predominant mineral. In the former case clear pistacites (largely euhedral) dominate strongly, clinozoisite and zoisite being rare. In the latter case dark hornblende predominates over the normal type. Only normal tourmalines occur. The zircons are euhedral; subhedral types are rare. All metamorphic minerals are present in varying amounts, but kyanite and chloritoid are rare in most slides. As a result of the scarcity of heavy minerals in the fine sediments of the inner part of the ria, the assemblages in the central part of this association are unknown. The three fields in the corners are considered as locally determined sub-associations.

Las Sinas sub-association. At station 588 the ratio of dark to normal hornblende is 2, and pistacite dominates slightly over clinozoisite. The other two samples contain equal amounts of dark and normal hornblende, and the ratio of pistacite to clinozoisite is about 3. The zircon content of these muds is low.

Con de Navio sub-association. Samples 650 and 651 have equal amounts of normal and dark hornblende; the epidote consists mainly of clear pistacites; sphene reaches 1%. The epidote group of stations 528 and 529 is largely made up of euhedral pistacite; normal hornblendes predominate slightly over the dark types, and sphene is the third important mineral. Zircon is the main mineral of the finest fraction: 45% for station 529 in the 75 to 50 micron fraction. At stations 532 and 351 clinozoisites are still rare, but only a small part of the clear pistacites is euhedral; there are equal amounts of dark and normal hornblende, and sphene is present. Normal hornblende dominates again over dark hornblende in samples 861 and 863; pistacite still predominates over clinozoisite, but almost euhedral grains are rare and sphene is absent.

Chazo sub-association. Station 384 fits in the preceding sub-association: clear pistacites strongly dominate and the ratio of the two types of hornblende is 1. Station 387, on the other hand, can be linked with the Las Sinas sub-association, because here most of the hornblendes are dark and pistacite predominates only slightly over clinozoisite. The percentages of the other two stations exceed the general ranges of the association. The metamorphic group (in particular staurolite) and the strongly coloured garnets are rounded to a high degree (cf. the Oceanic association); disregarding of these minerals brings station 389 into the Las Sinas and station 869 into the Con de Navio sub-association.

BARBANZA association. Percentage ranges: metamorphic group 56 to 85%, hornblende 1 to 7%, garnet 1 to 5%. Andalusite dominates strongly in the metamorphic group. Hornblende is entirely of the normal type. Most of the garnets are faintly pink; yellowish-brown garnets are found occasionally. Normal tourmalines predominate, dark types reach 0 to 2%; blue tourmalines are rare and purple ones were found in only two samples. All zircons are euhedral. The ratio of turbid pistacite to clinozoisite is variable; zoisite is rare. The association is subdivided into two fields:

Merced sub-association. In the metamorphic group andalusite reaches 45 to 84%. Stations 68 and 872 contain as much dark as normal hornblende and some kyanite grains; all the other samples lack dark hornblende and kyanite. Tremolite(?) occurs in samples 82, 89, and 90, monazite in samples 68 and 90.

Palmeira sub-association. Andalusite ranges from 29 to 70%. Kyanite is rare. Dark hornblende is absent. Monazite occurs in samples 485, 492, 494, 497, and 498.* Spinel is present in most of the samples.

OCEANIC association. Percentage ranges: garnet (strongly pink, rounded to well rounded) 14 to 44%, hornblende 2 to 13%. Sampes 370, 371, and 373 contain 2% rounded yellowish-brown garnet. Part of the hornblende is rounded, but most of the coarse grains are not; dark hornblende is present in most of the slides. Tourmalines are mostly rounded; the dark variety is present in all the slides, and blue and purple tourmalines both reach 1%. Zircon is the main mineral of the finest fraction (cf. Plate 3); about half the zircons are subrounded, and most of these are sligthly reddish-brown. Staurolite and andalusite are rounded. Kyanite and sillimanite are present, chloritoid is rare. In the epidote group,

* Parga-Pondal (1935) described an extremely monazite-rich beach sand from Insuela (near Palmeira), with percentages varying from 10 to 30 and a preferential grain-size of 250 microns. Monazite is very rare in the slides of the nearby submerged sediment. Mechanical disintegration is unlikely, because monazite is quite resistant; it is even known from Precambrian sediments (Behr 1965).

pistacite predominiates slightly over clinozoisite; zoisite reaches 2%. Hypersthene is present in most of the slides. The ocean samples are rich in opaque minerals, which are concentrated in the finer fractions; the 75 to 50 micron fraction contains 40 to 60%.

UMIA association. Percentage ranges: hornblende 21 to 70%, metamorphic group 10 to 39%, kyanite 0 to 2%. Dark hornblendes equal or predominate over normal ones. In the metamorphic group andalusite dominates over staurolite. The association is further characterized by the presence of up to 3% sphene and up to 1% titanaugite. Dark tourmalines are sometimes present, blue and purple ones are rare. Zircons are abundant and generally dominate over the 75 to 50 micron fraction; they are all euhedral. Yellowish brown garnets are present in very small amounts. Clinozoisite and zoisite occur only occasionally; all other epidotes are turbid pistacites. On the basis of the decreasing influence of the heavy minerals of the Umia River, the association has been subdivided into several sub-associations:
Inner sub-association. Hornblendes range from 44 to 70%, and dark hornblendes occur 3 to 7 times as much as the normal types. Kyanite and chloritoid are absent. Sample 950 shows staurolite-andalusite rock fragments. Zoisite is absent. All the samples contain sphene and titanaugite. Alterite percentages are very low: 1 to 3.
Central sub-association. Hornblendes range from 33 to 54% and dark ones are 1 to 2 times more abundant than normal hornblendes. The total percentages for the metamorphic group remain low, but kyanite occurs in amounts up to 2% and chloritoid is found occasionally. Titanaugite is present in all but two samples; sphene is less frequent.
Outer sub-association. Hornblende percentages continue to decrease, being 21 to 43; dark and normal types are found in about equal amounts. This decrease is accompanied by an increasing amount of metamorphic minerals: 20 to 39%. Kyanite accounts for up to 2%, chloritoid for less than 1% in all the samples. All slides contain some grains of titanaugite and sphene.
La Toja sub-association. The hornblendes and the metamorphic group reach the same percentages as in the Central sub-association; chloritoid is absent. Titanaugite and sphene are present in all the samples.

AROSA association. Percentage ranges: metamorphic minerals 36 to 95% (kyanite 1 to 22%), hornblende 0 to 12%. Staurolite predominates over andalusite in the metamorphic group. Normal hornblendes are equal to or predominate over dark hornblendes. Dark tourmalines are absent in about half of the samples but reach 2% in others. Partially blue tourmalines account for up to 3%; indicolite is less frequent and the purple tourmalines are rare. Zircons are almost exclusively euhedral and form the dominant mineral of the 75 to 50 micron fraction. Yellowish-brown garnets are found only occasionally. Pistacites predominate slightly over clinozoisites. The main area of the association is divided into two parts by the Isla de Arosa; the Umia association separates it from the El Grove sub-association.
El Vado sub-association. The entire metamorphic group ranges from 61 to 95%. Kyanite, the most conspicuous mineral of this area, reaches 2 to 22%. Chloritoid and zoisite are rare minerals in this sub-association. Sillimanite aggregates are present in the samples taken near the El Vado spit. Green spinel is present in most of the samples. Stations 185 and 724 are the only places in the ria at which faintly blue spinels were found.
Jidoiros sub-association. The metamorphic group comprises 36 to 61% of the heavy minerals. Kyanite amounts to 1 to 5%, chloritoid is absent. Zoisite accounts for up to 2%. Dark hornblende is rare. Spinel is absent in this area.
El Grove sub-association. Metamorphic group 44 to 60%, kyanite only 1 to 2%. Chloritoid, zoisite, and spinel are present.

The minerals of the titanium-oxide group have not been mentioned for any of the associations because they are accessory in all. Anatase is the most frequent, and sometimes reaches 3 to 5%. Rutile and brookite are less common.
Some individual assemblages (for example those of stations 101, 276, and 856) are not included in the associations described above: they are determined by very local influences. Most of the other assemblages, in particular those in the outer part of the ria, display mixing of all surrounding associations. This will be clear from an inspection of Plate 2.

Heavy-mineral transport and deposition

In this section we shall try to explain the distribution of the associations described above. The reader is once more referred to our Plates 2 and 3 and Figs. 1 and 2 from Floor (1968).
From the foregoing (page 98) it is clear that the Ulla River is at present incapable of transporting coarse sediment. The lower course of the Ulla itself shows estuarine characteristics (coarse-grained banks alternating with finer-grained deeper parts) and the muddy sediment of the inner part of the ria is found immediately at its mouth (Fig. 4). The bulk of the heavy minerals encountered in the investigated part of the river course must therefore have been brought and deposited there long ago. Because of the extensive drainage area of the Ulla River, a wide variety of minerals can be expected. Several assemblages indeed have about equal amounts of all the important minerals.
Most of the hornblendes of the Ulla association are very turbid, discoloured, and severely affected by weathering. They may have left the weathering zone in this condition, but frequent subaerial exposure in the river environment may have intensified these properties. Dark hornblendes cannot have been supplied by the Caldas granite, because the northernmost outcrops of these post-Hercynian granites are found south of

the river mouth. Indeed, these dark hornblendes are not of the same type as, for example, those from the Umia association, but are brownish-green and less deeply coloured. In the counting procedure such small differences between similar varieties were not distinguished.

At stations 755 and 838, samples were taken with a Dachnowski boring apparatus at depths of up to 8 and 5 m, respectively. The heavy-mineral assemblages of the uppermost samples are shown in Plate 2. The results of the deeper samples are not given because they show no important differences from the top sample, thus indicating that uniform sediment has already been accumulating in the middle of the river mouth for a considerable time, the rate of sedimentation being low.

Fine-grained Ulla material determines the assemblages of the muddy sediment of the inner part of the ria, most probably as a result of epithalassis (Conaghan 1966) during the winter months. The samples taken near the coasts belong to quite different associations and are only slightly influenced by the Ulla River (Arps & Kluyver 1968). The deeper stations generally contain insufficient heavy minerals. The assemblages of stations 60 and 663 would have belonged to the Ulla association had the percentage ranges been taken only a trifle wider. A deviation from the association's properties is the high content of dark hornblende in sample 663. An explanation of this content was supplied by local sailors: the material dredged from the harbour of Villagarcia de Arosa is usually dumped in this area.

The 'total' assemblage of station 856, which is situated between islets composed of paragneiss, seems to be in full accordance with the local petrology, and the 75 to 50 micron assemblage shows no relationship to the Ulla association. The presence of almost exclusively dark hornblende (in particular in the coarser fractions) as well as of clear pistacite, and the abundance of zircon in the 75 to 50 micron fraction (cf. the Rianjo association) show, however, that some of the minerals derive from the nearby Caldas granite.

It will be clear that the Beluso River, which is so much smaller than the Ulla, can have no influence at all on the Abanqueiro association. This is demonstrated in particular by the mineral titanaugite. In the lower course of the Beluso River titanaugite is present everywhere, but in gradually decreasing amounts (Arps 1965). About 100 m north of station 132, 6% titanaugite was still counted (Arps & Kluyver 1968) but only just under 1% is present at station 132, and it does not occur in any of the other samples of the association.

The assemblages of both associations in the Ria de Abanqueiro show greater individual differences than the samples from the other associations in the ria. All assemblages of the very small rivers draining the land around Rianjo are dominated by tourmaline and garnet (Arps & Kluyver 1968), but the outcropping rocks at the coast here consist of a wide variety of schists and gneisses with abundant lenses of basic rocks, and the assemblages appear to be determined by these local conditions. There is therefore no evidence of transportation, even on a small scale.

Dachnowski borings were made within the Rianjo association at stations 853, 883, and 897. The last two series of samples displayed uniform assemblages down to 6 and 10 m depth, respectively; the total thickness of the sediment here is unknown.

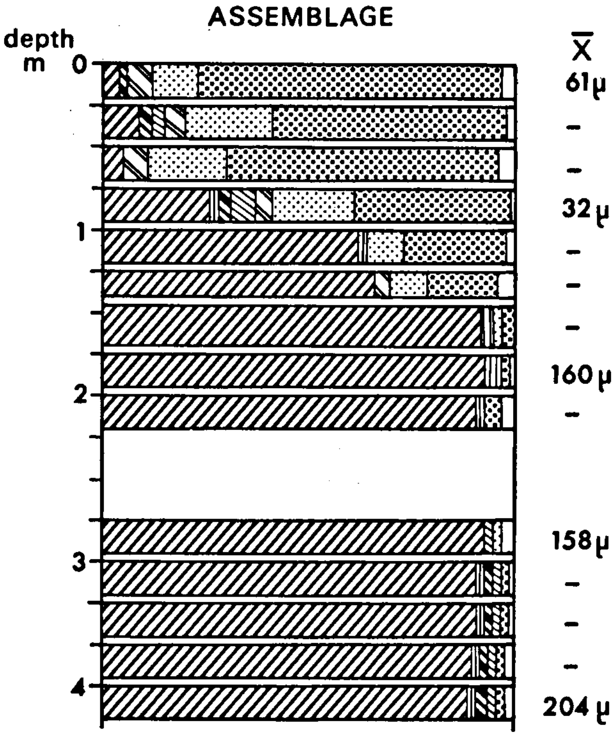


Fig. 17. Heavy-mineral assemblages of profile at station 853.

An interesting change, however, is noticed in the profile at station 853 (Fig. 17). The sediment from depths of —1 to —4 m (hard rock was struck at 4.20 m) belongs to the Abanqueiro association; 10 to 15% of the tourmalines is of the dark type and most of the zircons are subhedral or subrounded. In the top metre, normal hornblende is the dominant mineral and the zircons are euhedral. Although the grain-size decreases upwards, the difference in assemblages is not a result of this decrease. Owing to the small size of the samples, the material — after separation of the heavy minerals — was insufficient for grain-size analysis of all but five samples. The five calculated means point to an upward-decreasing grain-size, but the fractional analyses of samples 254 and 394 (Plate 3) have already shown that these small grain-size differences have no important influence on the assemblages. The entire profile thus forms a true provincial succession (Doeglas 1940, 1952). The deposition of the first three metres must have taken place before the inundation of the ria had been completed; deposition of one metre of fine material directly from the Ulla River or from the recent nearby beach took place thereafter.

The granite type containing dark hornblende is found in particular in the outer regions of the Caldas intrusion, and supplies this most characteristic mineral of the Caldas association. High-grade metamorphic xenoliths are also found in these parts of the intrusion; being unevenly distributed, their minerals are represented in varying amounts in the assemblages. Even more locally restricted are epidote-quartz veins giving rise to the exceptional amounts of euhedral pistacites and sphene in the Con de Navio sub-association.

It has already been mentioned (page 106) that two samples from the Chazo sub-association (389, 869) are composed mainly of material derived from an old beach deposit. This is the only place where obvious mixing with subrecent (reworked) material was found in the bottom sediment at a place so far up the ria. The complete absence of 'oceanic' minerals at nearby stations 384 and 387 constitutes evidence that transportation of sand grains does not take place even on a very restricted scale. The beach assemblages from Cabo Cruz to Chazo (Arps & Kluyver 1968) resemble our stations 77 and 79.

The petrology of the NE part of the Barbanza peninsula is dominated by micaschists, resulting in the extremely andalusite-rich assemblages of the Merced sub-association. The SW part, on the other hand, and particularly the coastal region from Palmeira to La Covasa, consists mostly of Caldas granite. Andalusite therefore decreases gradually in this direction; the same trend has been noticed in the beach sands by Arps & Kluyver (1968). Staurolite and hornblende increase in the same direction, but the latter is not of the dark type. Hypersthene is present in sample 827, in the samples from all the stations in the direction of La Covasa, and further towards the Isla de Salvora, including samples 814 and 815. A variable degree of roundness of staurolite, andalusite, garnet, etc.; the presence of hypersthene; and the paucity of heavy minerals in the local Caldas granite, strongly suggest that the sediment of the coastal area between the Palmeira sub-association and the Oceanic association derived mainly from the ocean. Since the force of the ocean waves is broken by the island-arc stretching from La Covasa to the Isla de Salvora, the sand could not have been transported directly by a tidal current. More probably it was carried by the wind from local dunes on the SW part of the Barbanza peninsula (Arps & Kluyver 1968).

Perez Mateos investigated the heavy-mineral content of some samples from the Galician continental slope (see: Gonzalez Peña 1958). His sample nr. 4, taken at a depth of 112 m before the Ria de Arosa, fits into our Oceanic association. The assemblage of this sample contains 24% almandites and 75% opaques.

Detailed heavy-mineral analyses from weathering profiles in the Caldas granite and its traversing rivers have been made by Bisdom (1965). As outlined on page 113, the Umia association, which differs clearly from the adjacent Arosa association by the presence of dark hornblende, titanaugite, and sphene, can be traced even into the outer part of the ria.

Upstream in the Umia River the metamorphic minerals are dominant. As it flows through the hornblende-bearing granite, the amount of dark hornblende gradually increases to 40% and then remains constant (Bisdom 1967b) until it again increases in the downstream section sampled by the present author. Dolerite dykes are locally present in the central part of the intrusion; in all probability, small tributaries of the Umia River bring in titanaugite and sphene deriving from these dykes.

At first sight it seems strange that this association, which is determined by material supplied by a river smaller than the Ulla, influences the bottom sediment of the ria more strongly than does the Ulla association. There are several possible explanations for this discrepancy. In the first place, the accumulation of muddy sediment (a continuous process) in the inner part of the ria is somewhat higher than in the area of the Central and Outer sub-associations of the Umia association (cf. Ch. VIII), which is one reason why the counting of heavy minerals in the inner part of the ria was impossible. Secondly, the Ulla River flows into a vast shallow area. The Umia River, to the contrary, enters the ria at a place where there is a depression with depths over 20 m, which results in longer settling times for the very fine sand grains. If these grains do not settle before reaching the narrow passage between the Isla de Arosa and El Grove, they are carried into the outer part of the ria with the low-water tide (cf. Nonn 1966, lefthand part of Plate 14). The phenomenon of floating sand (Wolf 1961), which is frequently observed in the Umia estuary, might also be significant.

Finally, we may turn our attention to the Arosa association with its conspicuously metamorphic character. The Isla de Arosa and the coastal area between Villanueva and Cambados lie in the centre of the Caldas intrusion and are composed mainly of biotite-muscovite-granites. Xenoliths are much less frequent than in the outer regions of the intrusion and do not contain high-grade metamorphic minerals. They are present in appreciable amounts, however, in the colluvia over the saprolites. But Bisdom (1967b), after comparing the heavy-mineral assemblages of some series of samples taken along a line running inland from the coast, concluded that these minerals had been blown in from the Arosa association, most probably in periglacial times. Two strong arguments support this theory. Firstly, the assemblages of the colluvium samples show a close resemblance to those of the Arosa association, and the proportion of metamorphic minerals decreases going inland. In the second place, the transport of blown sands up to heights of more than 100 m above sea-level can still be observed on the El Grove peninsula and south of La Lanzada (Bisdom-Dedert 1966).

So the question remains, where does the material of the Arosa association originate from? Because it cannot have derived from the mainland in recent times and sedimentation in this shallow area at present is quite unlikely, this association must be older than the Caldas and Umia associations. For an explanation in terms of

a marine or fluvial derivation, the presence of so much kyanite is very embarrassing.
The Arosa association has only a few metamorphic minerals in common with the Oceanic association, and these minerals have different specific properties. Only for the Jidoiros sub-association could some oceanic influence be assumed, and perhaps also for the samples around El Grove but there mainly from sand blown in over the peninsula. The El Vado sub-association, however, has not only low roundness values (cf. Fig. 15) but also too much kyanite, and lacks the strongly coloured oceanic garnets.

Various assumptions could be made to interpret the sediment around El Vado. One possibility is that shifts took place in the direction of the flow of the Umia River. Another concerns weathering: during the last regression of the sea the area must have been exposed to the air; chemical destruction of all hornblendes and epidotes, if that took place, would have left metamorphic assemblages behind; and after the final inundation, small amounts of Umia material could have been added again. Hornblende and epidote are indeed concentrated in the finer fractions here (cf. Plate 3), and their properties are the same as those of the Umia association. However, it is dubious whether chemical weathering could have produced these effects: alterites are not abundant and staurolite, which is not resistant to weathering either, still dominates over andalusite. A third assumption is that the association derived from some now submerged outcrops of metamorphic rocks. The real source of the Arosa association remains obscure, however.

LIGHT MINERALS

Slides of the 500 to 50 micron light fraction of 27 samples were prepared according to Vogel (1965). The low refractive index ($n = 1.529$) of the immersion liquid (Lakeside) facilitates the distinction between the different feldspars. In each slide 250 grains were identified under the monocular polarizing microscope (with the exception of slide 503, which contained only 81 grains).
The properties of the minerals encountered are as follows:

QUARTZ. Almost all the grains show undulatory extinction as the main distinctive feature. Refractive index higher than Lakeside. Interference figures not always conclusive. Polysegmental quartzes rare; when present, they consist of more than 5 grains. The degree of incipient fracturing of quartz crystals depends to a high degree on local stress conditions in the cooling granitic body (Moss 1966; cf. page 107). Two of the slides showed a large quantity of very small quartz grains, which makes it highly probable that these quartzes disintegrated during the preparation of the slides.

PLAGIOCLASE is present in all the slides (2 to 12%). Refractive index higher than Lakeside. Almost all the grains are slightly sericitized, some even strongly so, and could rarely be distinguished from other minerals on the basis of polysynthetic twinning.

POTASH FELDSPAR. Refractive index lower than Lakeside. (a) With lattice structure (microline), comprising about 5% in almost all the slides. (b) Without lattice structure. Occasional twinning (orthoclase). These feldspars occur the most frequently and range from 7 to 37%.
Feldspars that could not be further distinguished because of advanced alteration are extremely rare.

MICAS were identified by their typical 'bird's eye' structure. Some untreated samples, particularly those from the Umia River, glitter due to the presence of micas, but these micas occur chiefly in the size-range above 1000 microns. In the 500 to 50 micron light-mineral fraction, micas reach only 3% and probably consist mainly of muscovite. Bleaching of biotite proceeds rapidly in the weathering profile, and bleached biotites could not be reliably distinguished from muscovites in the slides.

CHLORITE. These weakly pleochroic green grains occur occasionally in the slides. One sample (195) is exceptional: removal of the carbonates and organic material left a bright green sand, possibly composed mainly of (badly crystallized) chlorite. An X-ray photo was made of this material. The line pattern resembled that of glauconite, however, but without the 10.0 Å and other decisive reflections.

We have no explanation for the abundance of this material at this station. There are many favourable conditions present for the formation of glauconite pellets, but none were encountered, possibly because the temperature of the bottom water of the ria (about 15°C during most of the year) is too high for the development of well-crystallized glauconite (Porrenga 1967, p. 98). This mineral is also discussed in the section on clay minerals.

Quartz and total feldspar were recalculated to 100%; the ratios are presented as circular diagrams in Fig. 18. This system was used for Mediterranean beach sands by Giresse (1965) to obtain a comprehensive picture of the relation between the two main constituents of the light fraction: quartz and feldspar. Our results fit perfectly with the mineralogical composition of the rocks exposed in the area. The arkosic composition of most of the samples reflects their granitic origin, but in the weathering profiles the ratio feldspar/quartz in the 500 to 50 micron fraction is still higher: 3 to 8 (Bisdom 1967b). A high quartz content is found in three regions: the inner part of the ria, the area around El Vado, and in the ocean.

With respect to the inner part of the ria, we know that the Ulla River flows mainly through metamorphic rocks. The Ria de Abanqueiro is also surrounded by rocks consisting mainly of paragneiss. All these rocks supply more quartz than do the granites, which results in a relatively lower feldspar content. As we have already mentioned in connection with the heavy minerals, the small islands lying on either side of station 856 consist of andalusite-rich paragneiss. An

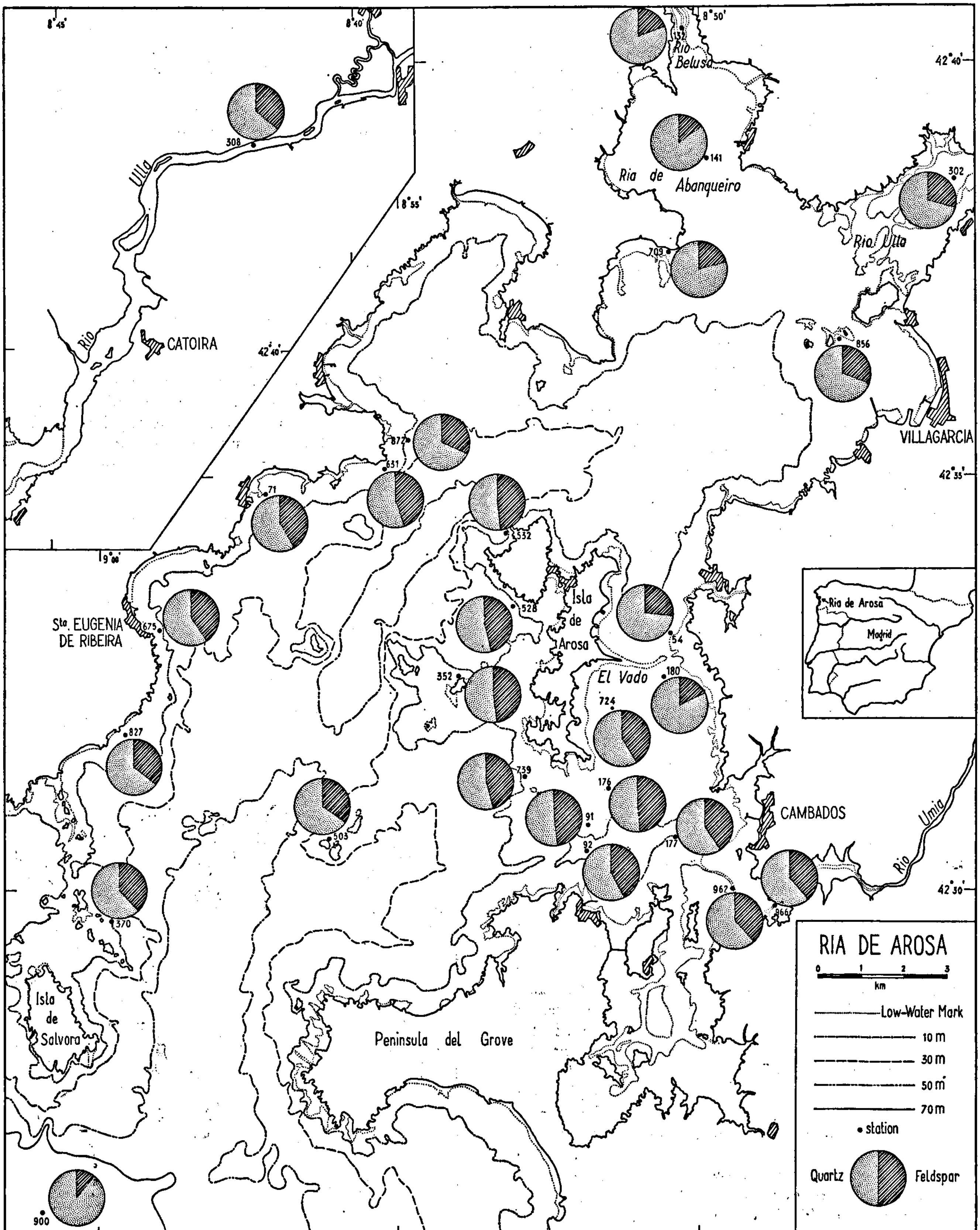


Fig. 18. Quartz/feldspar ratios of light-mineral fractions at 27 locations in the Ria de Arosa.

outcrop of the same rocks is found on the other side of the ria at station 872.

Concerning El Vado, this spit is dry at low-water over almost its full length, but it disappears completely at high-water. This regularly recurring exposure to the air may result in the chemical destruction of the feldspars (Kuenen 1959), thus causing the lower feldspar percentages of samples 54 and 180. In general, the ratio quartz/feldspars is slightly higher in the shallow-water samples than in the deeper deposits.

The sediment sampled in the ocean at station 900 may derive only partly from the ria area. This possibility has already been indicated by the different degree of roundness mentioned on page 107.

CHAPTER VIII

SEDIMENTOLOGY OF THE NON-CALCAREOUS FINE FRACTION

PHYSICAL ASPECTS

The muds and sandy muds encountered in the Ria de Arosa show three mutually related physical aspects: odour, colour, and water content.

Reducing conditions exist in the top layer of the bottom sediments of the inner part of the ria. In this area the muddy sediments smell strongly of hydrogen sulphide, appear black with a dark green luster, and are extremely soft (high water content). The line drawn in Fig. 19 in the central part of the ria indicates a sharp olifactory boundary: the hydrogen sulphide smell disappears abruptly south of this line. The water content of the muddy sediments decreases rapidly in the same direction, and the colour gradually changes from dark grey (prevailing in the rest of the muds) to greyish-green (prevailing in the sandy muds of the outer ria). The bulge in the boundary line suggests that below water depths of more than about 50 m the muds of the central part of the ria are better oxygenated than the shallower bottom sediments. Vertical convection is less important for the replenishment of oxygen than the bottom currents flowing in from the ocean into the ria.

Exact measurements of the water content of the muds could not be made; grab samples are generally disturbed and coring causes compression of the sediment. Divers noticed that in the inner part of the ria the sediment/water interface was disturbed by the slightest motion. Within less than half a metre the mud becomes abruptly firmer. Berthois & Calvez (1961) measured the water content of core samples of black clays in Sangaréa Bay, Guinea: the top layer of their cores contained up to 150% water with respect to the clay; in the first 20 cm this content initially decreased slowly and then dropped to 75% at 30 cm depth in the sediment. In a more open marine environment this 'soupy mobile layer' (Emery & Rittenberg 1952, p. 751) is reported to be only 2.5 cm thick. In the very quiet inner part of the Ria de Arosa the abrupt decrease might take place even deeper in the sediment than 30 cm. The absence of water currents and the low rate of sedimentation allows the random settling of clay and silt particles on top of the sediment, leaving large interspaces filled with water. After burial, this structure will eventually collapse like a house of cards under the pressure of the overlying sediment.

The depth range of the reducing conditions is even more difficult to estimate. Cadée (1968, p. 19) reports that zero values of oxygen were not measured anywhere in the bottom water, since all the water samples were taken at about 50 cm above the sediment/water interface. In five grabs in which the top layer of the sediment was obtained undisturbed, the upper few millimetres were oxygenated (brown coloured). The

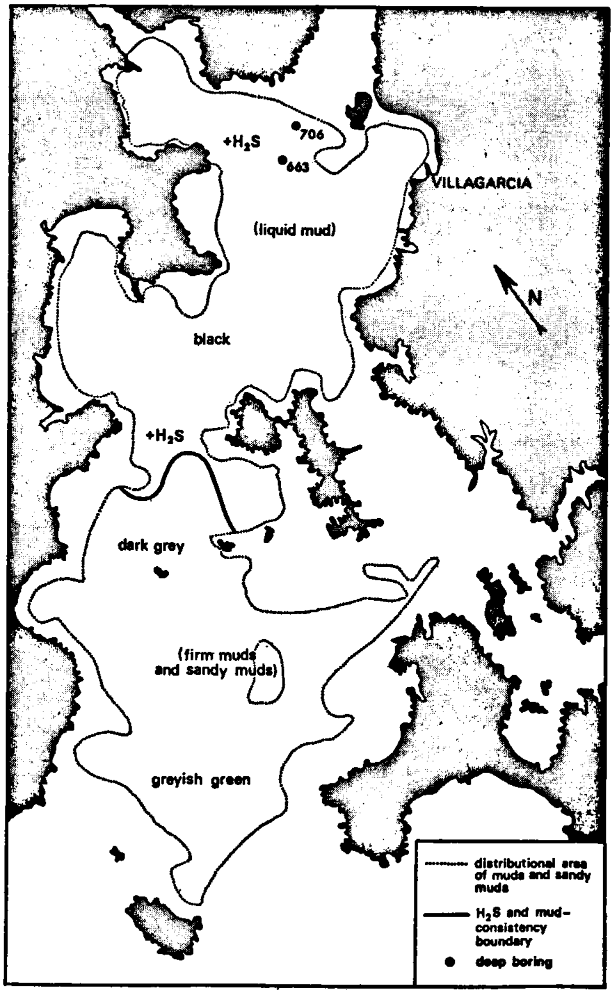


Fig. 19. Physical properties of muds and sandy muds.

situation of this upper boundary of the H_2S-zone changes with the season, and we assume that it may sometimes even reach the sediment/water interface. The lower boundary of the H_2S-zone lies fairly deep. At station 663 (see Fig. 19) a boring was made 10 m in the sediment. In this series of core-samples the odour was strong in the upper 3 m and then became imperceptible within the next metre; from —4 m onwards the boring supplied firm grey odourless mud. Except for these physical differences the sediment is uniform over the total length of 10 m; uniformity was also shown by all the punch-cores. The clay mineralogy does not change qualitatively with depth, as evidenced by five samples studied from the second deep boring at station 706 (see page 126), and the grain-size does not vary within one metre (analyses of several cores taken at stations spread over the whole bottom of the ria).

Lamination was not seen on the X-radiation photographs made of all cores and borings; only some of them showed mottling. According to Pantin (1966, p. 59), unlaminated mottled sediments from Hawke Bay, New Zealand, result particularly from repeated disturbance by the epifauna (animals living on the seabed). Lamination, on the other hand, should be found in areas where the epifauna is poorly developed as a result of deficiency or absence of oxygen. Such laminated muds have been encountered in some parts of the Adriatic Sea, for example (Van Straaten 1966), but they were not found in the inner part of the Ria de Arosa, where similar conditions are present. Apparently, the rate of sedimentation in the ria did not vary appreciably with time. Although during periods of heavy rainfall the river must inevitably supply at least coarse silt particles, the simultaneous increased discharge of the river would probably stir the 'soupy mobile layer' and thus prevent formation of coarser-grained lamina.

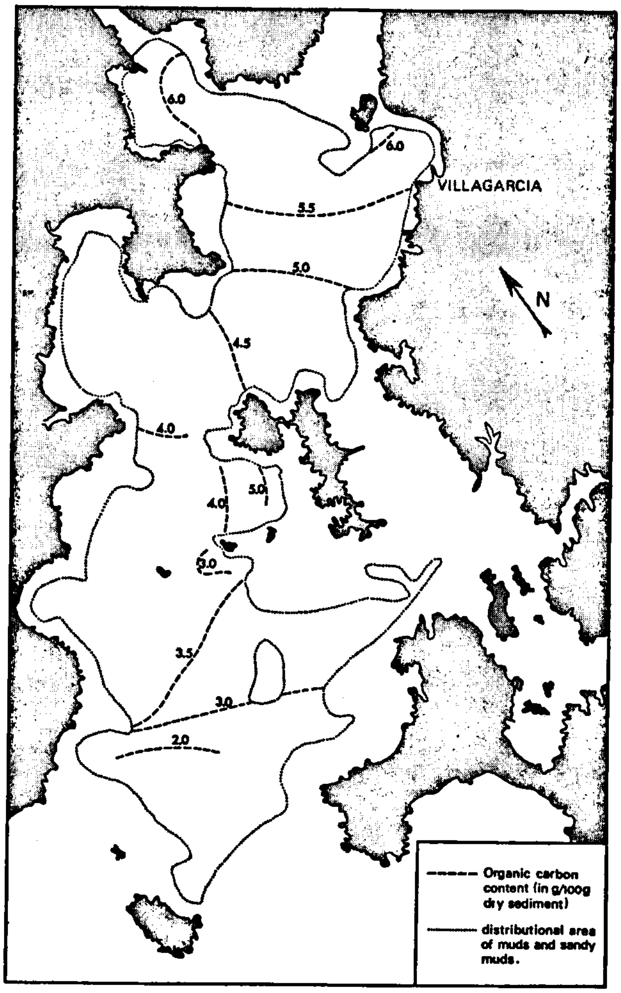


Fig. 20. Organic carbon content of muds and sandy muds (after Cadée 1968).

CHEMICAL ASPECTS

The causes of the many colour differences encountered in marine muds cannot always be satisfactorily explained. Greyish-green seems to predominate. Very dark grey and black tones are accompanied by reducing conditions and better preservation of organic matter (Kaplan & Rittenberg 1963, McCrone 1966). Black colour is generally related to either high contents of organic matter or with finely disseminated iron sulphide (Krumbein & Sloss 1963, p. 124). We will discuss both possibilities.

The organic carbon content of the muddy sediments of the Ria de Arosa has been analyzed by Cadée (1968), who kindly permitted the present author to reproduce his results. Cadée's Fig. 16 is slightly modified in our Fig. 20 in that his 40%-mud boundary has been replaced by the 50%-mud boundary used throughout this study. This map shows that the organic carbon content gradually decreases from the inner part of the ria toward the ocean. Phytoplankton is the main source of the organic matter; minor contributors are plant debris (only important in the innermost part of the ria; Cadée *ibid.*, p. 17) and organic matter enclosed in mixed-layer clay minerals (Bisdom 1967b).

During part of the year the production of phytoplankton is high in the inner part of the Ria de Arosa, and preservational conditions for organic matter are moreover favourable there. The production depends on the supply of nutrients, and this supply is favoured by the upwelling occurring near the Galician coast from March to November (Korringa 1967). The phenomenon of the increasing accumulation of dead plankton toward the inner part of this type of bay has been discussed by Brongersma-Sanders (1965). The preservation of organic matter is especially favoured in the inner ria by the paucity of epifauna consuming the matter and by the fineness of the sediment (cf. Guilcher & Pruleau 1963, Kaplan & Rittenberg 1963). Cadée (1968, p. 18), in summarizing the factors influencing the high organic carbon percentages of the inner ria, includes a higher rate of sedimentation among these factors. However, although this rate is indeed higher than in the outer part, it is still quite low. A high rate of sedimentation, to the contrary, would actually cause a relative dilution of the available organic matter (Biggs 1967).

The black colour of marine muds may also be caused by the presence of amorphous ferrous sulphide, known as hydrotroilite. The formula of hydrotroilite is not known exactly, because its peaks on X-ray diffractograms are masked by high-order reflections of certain clay minerals (Berner 1967); it is generally written as $FeS.nH_2O$. In an oxydized environment it may gradually transform into its disulphide (Biggs 1967). Clear pyrite reflections have not been found in X-ray diffractograms of samples from the outer part of the ria. On the other hand, even a very small quantity of hydrotroilite would be sufficient to colour the muds of the inner ria. Although the amounts of vermiculite, and possibly of septechlorite, may be sufficient to account for the rather high percentages of total iron measured in the muds of the ria (Table V), we may not exclude the presence of hydrotroilite.

As long as the real nature of neither this ferrous sulphide nor these organic compounds is well understood, the actual cause of the black colour of certain marine muds cannot be explained with certainty.

Seven samples were subjected to an X-ray fluorescence analysis (Porrenga 1967, p. 20) to determine the chemical composition of the clay fraction. The results for the major elements are shown in Table V. Sample 917 was taken from a small abandoned channel of the Sar River (confluent to the Ulla) and 915 from the Ulla River itself. Sample 706.1 is taken at a sediment-depth of 3 m from the deep boring at station 706. The next two stations lie in the inner part of the ria, 456 in the outer part, and 901 in the Atlantic (see Fig. 23).

Anticipating the clay mineralogy in following sections, we may deduce some trends from Table V. Increasing concentrations are found for CaO and for MgO, which may be connected with the montmorillonite content of the clays. Potassium also increases toward the ocean; this may be ascribed to regrading of illite.

Titanium percentages decrease from the Ulla River toward the inner part of the ria and then remain constant; this may be connected with the presence of kaolinite. The ratio Al_2O_3/TiO_2 increases in the same direction from 28 to 40, which gives evidence of the relative influence of basic rocks on the composition of the river sediments as compared to the mainly granitic origin of the ria deposits (cf. Porrenga 1967, p. 55). Conspicuously high percentages are found for P_2O_5, also decreasing in the direction toward the ocean. We assume that this oxide results from the disintegration of land-derived apatite.

GRANULOMETRICS OF MUDDY SEDIMENTS

Introductory remarks

The validity of grain-size analysis of muddy sediments obtained by the pipette method has been questioned by many authors (Griffiths 1957, Whitehouse *et al.* 1960, Duane 1964), mainly because of the discrepancy between the behaviour of the finest particles in the natural environment and in the laboratory. Without going into details, we may mention the flocculation process of clay minerals settling in saline waters, a reversible process; the kind of aggregates that may arise during the pipette analysis as a result of peptonization differs from the floccules occurring in the natural environment (Yañez 1963).

In the case of the muds of the Ria de Arosa there is one other possible disturbing factor. After treatment with hydrochloric acid a very fine residue of the (large) bioclastic fraction may be included in the pipette analysis; this contamination may give an erroneous increase of particularly the weight fraction smaller than 2 micron (Pilkey 1964).

The nature of these sediments and their origin can therefore be studied better by investigating their petrological composition. Notwithstanding the drawbacks mentioned above, however, certain properties of the grain-size distributions of the muddy sediments may supply reliable information regarding their origin, particularly when the finest fractions are mixed with sandy components.

Moment measures of the grain-size distributions of muds and sandy muds were calculated, but the results have no environmental significance. The means range from $+7$ to $+8\frac{1}{2}$ phi. Because most grains are concentrated in the finer silt fractions and the undifferentiated clay class, and the distributions display a tail toward the coarser end, the other measures may be predicted. Skewness will normally be negative and, in the case of bimodal distributions, variable. Sorting of the meso- or platykurtic curves will be very poor to extremely poor, as can already be seen from Fig. 14. A better way to approach these sediments is, therefore, to attempt to find an explanation for grain-size modes (Curray 1960b). The muds (which are not included in Fig. 14) all show one mode, either in the 18th or in the 19th fraction (cf. Table I). This very small variance probably results from the analytical technique; there is no relation between the position of the mode in the curve and the situation of the sampled stations in the ria. We may therefore conclude that the deposits in all parts of both mud areas (Fig. 4) are uniform.

The often bimodal distributions of sandy muds in the Ria de Abanqueiro, in the Ensenada de la Merced, and before Sta Eugenia de Ribeira, have already been treated in the preceding chapter together with coarser sediments. The vast area of sandy mud in the outer part of the ria will be discussed below.

Fine sand in the ria derived from the ocean

The frequency distributions of seven samples from the outer part of the ria are shown in Fig. 21. The coarse sandy mud of sample 479 is slightly polymodal; all the others are distinctly bimodal with one mode around the clay-silt boundary ($= +9$ phi; equal to the muds) and another one in the fine sand range.

Agglutinations of flocculated clay minerals may reach this size under certain conditions (Rogers 1959, Schneider & Heezen 1966), and some organisms can produce such sand-sized clay aggregates. However, inspection of these fractions after grain-size analysis showed that they consist of normal fine quartz-particles.

It is evident from the course of the curves that these sandy muds are mixed sediments. In other words, the boundary line in the outer part of the ria in Fig. 4 (page 90) is not taken arbitrarily in a field of gradually coarsening bottom sediments in the direction of the ocean. We assume that under normal weather conditions mud of uniform granular composition is deposited in the central and the outer ria alike. The origin of this mud and the directions of transport will be discussed in the next sections.

The second, coarser mode in the frequency distributions is conspicuously situated at the same place, i.e. the 12th fraction, for samples 278, 480, 930, and 478. It is assumed that during times of certain extreme weather conditions the bottom current is just able to carry small amounts of fine sand into the ria. The deposition of these grains is mainly limited to the eastern part of the basin because of the Coriolis force, which explains the bulge in the mud/sandy mud boundary line in Fig. 4 in the western part, where only mud is deposited. The particles are forced to settle before the bottom current reaches the Central rise.

The Ocean rise lies at a depth of slightly less than 60 m, so the fine sand cannot originate from there. Its source must be sought in the shallower waters near the coasts of the El Grove peninsula and the Isla de Salvora. In these coastal sediments +3 phi-sized grains must be about the finest sand particles available. The course of the frequency curve of sample 479 is not in accordance with the other curves, particularly in that it does not display a distinct second mode. About equal amounts of all sand-sizes are present; even particles over —2 phi occur. This location is already too high to be reached by fine sand carried by the bottom current. The coarser constituents of sample 479 must have been derived from the nearby Los Mezos group.

CLAY MINERALOGY

Provenance of clay minerals

Guilcher (1967) recently discussed the various possibilities for the provenance of estuarine muds. The factors controlling differences in the sedimentation in

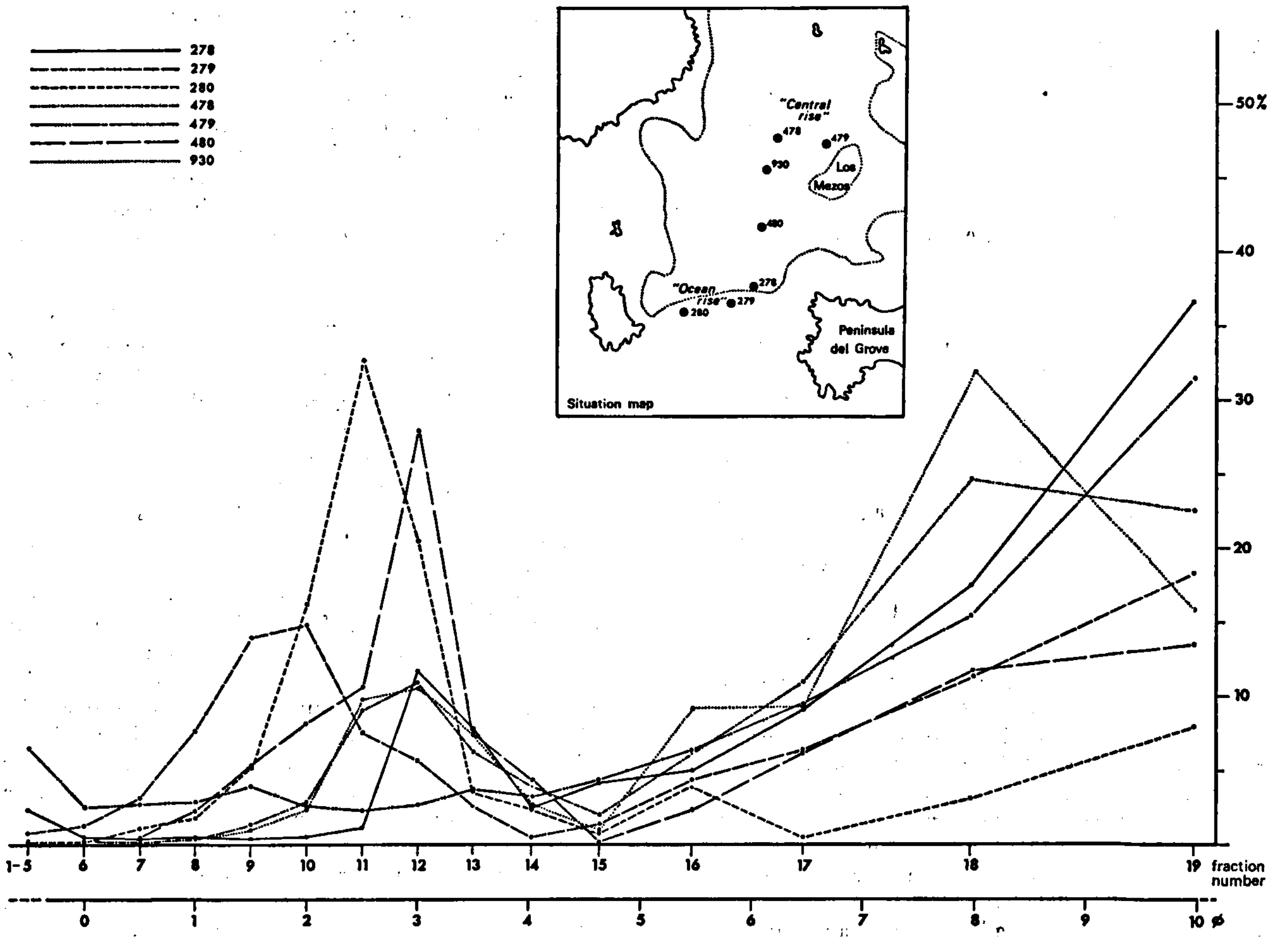


Fig. 21. Grain-size frequency curves of samples from the outer part of the ria.

estuaries belong, according to Guilcher, to two groups: (1) contrasts in discharge, and (2) water motion within the estuary.
In small estuaries with low discharge, mud from the oceanic environment may form an important constituent of the deposits in the bay. If the estuary extends far into the land, however, and particularly when the confluents have a high discharge, the muds will be almost entirely terrigenous. In the case of the Ria de Arosa, where the total influx of fresh water is small with respect to the total water mass and the bay is wide and long, the relative influence of fluvial- and ocean-derived mud is difficult to predict. Of course, it must be considered that even the mud in the Atlantic Ocean must have originally come from terrigenous detritus (Biscaye 1965) and been deposited there long ago, which means that it derived partially from the Galician coastal areas.

Before discussing the distribution of the clay minerals in the Ria de Arosa we may review the data in the literature of the last decade concerning the possible provenance of these clays.
Clay minerals from weathering profiles of the various rock types on the mainland NW of the Ria de Arosa have been studied by Arps & Kluyver (1968); samples were taken from the basis of the C-zone and from the top of this zone or higher in the profile. Gibbsite was found to be concentrated at the base of the C-zone, and appeared to be present in all types of rocks. Illite and halloysite were found in most granitic profiles but only in the higher zones. The presence of kaolinite and montmorillonite was demonstrated only occasionally in the megacrystal muscovite-biotite granite.
A detailed study on the weathering of the various mineral components of the Caldas granite has been published by Bisdom (1967b). Gibbsite is only stable in a highly alkaline environment (Grant 1966), and was accordingly found by Bisdom concentrated in micro-cracks in feldspars in their first weathering stage. In the saprock/saprolite transition-zone the pH decreases, and in the resulting slightly acid environment kaolinite and halloysite become stable. According to Bisdom, the kaolinite grains may reach a size of 1 mm. In the A-horizon acid conditions may be so strong that kaolinite decomposes again into gibbsite and silica. The reactions assumed to take place are described by Grant (1966). Biotite weathers into vermiculite; it could not be determined whether vermiculite changes into mixed-layer clay minerals in a further stage.

Furthermore, the clay minerals found in the bottom sediments of the Ria de Arosa could have derived from Quaternary deposits. Kaolin deposits, originally transported as a mud flow, containing 80 to 100% kaolinite, present at several places near the coasts of the ria have been described by Nonn (1966, p. 326).
Bakker (1963) published a map showing the types of clay minerals available in the land-masses surrounding the Atlantic Ocean, in which Spain carries the letters Imk, indicating that illite is the dominant clay mineral and that montmorillonite and kaolinite are less important. Gonzalez Peña (1958) described five samples taken at depths of between 100 and 500 m before the mouth of the Ria de Arosa. According to this author, kaolinite and illite are the main components of the clay fraction, and traces of halloysite and quartz are found; montmorillonite is not mentioned.
Hundreds of oceanic core samples, mainly from the Atlantic, have been investigated for their petrological composition by Biscaye (1965), who constructed contour maps for the various clay minerals based on p.a.p. (= peak-area percentages). These maps show that the clay fraction of the oceanic sediment along the coast of Galicia contains more than 50% illite and that kaolinite, chlorite, and montmorillonite all reach about 10%.

X-ray diffraction photos

A first approach for an estimation of the distribution of clay minerals in the Ria de Arosa was made by the inspection of X-ray photos of the clay fraction of 33 samples taken over the whole area. The positions of the stations at which these grab samples were taken are indicated in Fig. 23. Pre-treatment of the clay fraction is shown schematically in Fig. 3 (page 88). Photographs of non-oriented slides of the fraction smaller than 1 micron were made with a Guinier — de Wolff camera. A semi-quantitative interpretation of the results is given in Table VI, based upon four grades of relative intensities of the lines on the photographs. Kaolinite was determined from its basal reflections at 7.15 and 3.57 Å and some characteristic non-basal lines. Illite was identified from reflections at 10.0, 5.0, and 1.50 Å; the modification seemed to be 2M, which would indicate a metamorphic origin (Yoder & Eugster 1955). Illite was distinguished from kaolinite from reflections at 2.59 and 1.50 Å.
A reflection at 14 Å was tentatively ascribed to chlorite. One sample (525) was treated by heating to 270 and then to 400°C. After the first treatment the 14 Å-reflection became weaker, and at 400°C it had disappeared completely, which could indicate iron-rich chlorite or vermiculite. The term chloritic matter was preferred, because minor reflections did not reveal the real nature of the material.
Distinct lines at 4.85 and at 4.37 Å were identified as the (002) and (020) reflections of gibbsite, respectively.
Table VI and Fig. 23 show in the first place that kaolinite is abundant in four fluviatile samples. There seems to be an abrupt change in the estuaries of the Ulla and Umia rivers to a low kaolinite content; this content does not show marked differences over the whole ria. Illite appears to be present in all samples in fair amounts. The 14 Å-mineral is absent in the river samples, but a trace is encountered in the estuarine environment; it is present in all the ria muds. Gibbsite is only found in the inner part of the ria. Traces of quartz and feldspar occur occasionally.
The seemingly rapid decrease of the kaolinite content presents a problem. The difference in settling velocity between kaolinite and illite particles in the marine

environment is too small to account for the considerable relative decrease of kaolinite in the estuary (Whitehouse *et al.* 1960). If a fine-grained mineral like montmorillonite were involved, differential sedimentation could provide an explanation (Pryor & Glass 1961, Porrenga 1966). The presence of montmorillonite was not demonstrated because the samples prepared for photography were not treated with ethylene glycol. In the next section we will see that montmorillonite is indeed present, but in quantities too small to express differential sedimentation clearly.

Another possibility could be the conversion of kaolinite into another mineral, here presumably into chloritic matter. The possible conversion of kaolinite into chlorite under prolonged diagenetic conditions has been propunded by Orbell (1965). The results of practical experience (Stewart & Gorslin 1962, Rateyev 1963) and laboratory experiments (Whitehouse & McCarter 1958), however, lead to the conclusion that it is unlikely that such conversion takes place rapidly in a recent marine environment.

The absence of gibbsite in the samples from the main confluents of the ria, as shown by the data in Table VI, is questionable; this mineral may have escaped detection because of the abundance of kaolinite. Its restriction to the inner part of the ria may constitute evidence of a decreasing proportion of mud supplied by rivers in the sedimentation in the ria.

As a whole, the results obtained with this method of investigation leave many questions unsolved. To obtain a better idea of the clay mineralogy of the Ria de Arosa, some samples were sent to the laboratory of the Shell Research (Rijswijk Z.-H.), where oriented samples of the clay fractions were examined by X-ray diffraction.

Identification of clay minerals in X-ray diffractograms
Diffractograms were made of oriented slides of the fraction smaller than 2 microns. For the conversion of the diffraction angles into d-values we used Swanson's tables (1950, pp. 122—126). Identification was based on the various tables in Brown (1961). The minerals were distinguished according to their basal reflections as listed below; Fig. 22 gives an example to facilitate the inspection of the diffractograms depicted on Plate 4.

Feldspar. Traces of feldspar are indicated in most of the diagrams by very small peaks between 3.20 and 3.25 Å.

GIBBSITE. This mineral was identified by its (002) reflection at 4.85 Å. Although even small quantities can be detected, this becomes rather difficult when

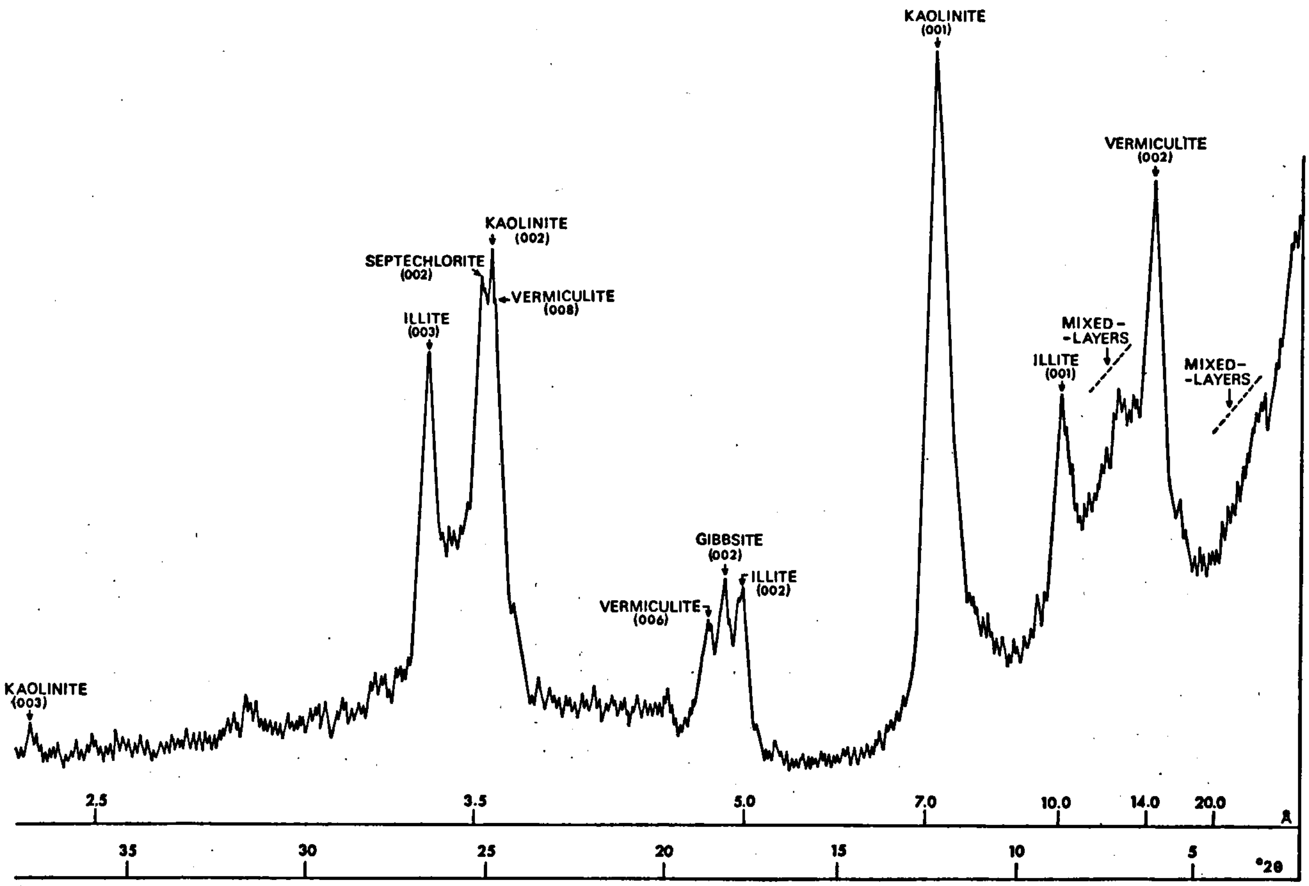


Fig. 22. X-ray diffractogram of sample 917 (glycolated).

relatively large amounts of chlorite or vermiculite are present. Gibbsite disappeared after heating to 300°C.

ILLITE. The structural classification of this mineral is still under discussion (Brindley 1966). According to Hower & Mowatt (1966), montmorillonite, mixed-layer illite/montmorillonite, and illites form a continuous mineralogical sequence, which implies that most illites show some swelling. In the present samples glycolation produced no shifts in the distinct peaks at 10.0, 5.0, and 3.33 Å; illite is used as a general term for this material in accordance with Gaudette *et al.* (1966), Porrenga (1967, p. 19), and others. The (004) reflection is weak, whereas the (005) peak equals the (003) peak in height (the original diffractograms were taken up to 45°2 θ with CuKα radiation). Some diffractograms were made of non-oriented slides, but the illite modification could not be determined.

KAOLINITE. Identified from its basal reflections (001) and (002); the peaks (at 7.16 and 3.58 Å, respectively) are less sharp than those of illite because of the reflections of other minerals having about equal spacings (see septechlorite and vermiculite). The (003) reflection is rather weak. At 300°C the peaks have become slightly lower and have disappeared completely at 550°C.

Mixed-layers. Although a trace is present in all samples, mixed-layers only occur in larger amounts in sample 917 (cf. Fig. 22). They were identified from an elevated base-line and several peaks in the 10.5 to 14 Å range. There are probably many different types of mixed-layers, but these cannot be distinguished, mainly because there are no distinct differences in the height of the numerous peaks at spacings above 20 Å. There is a slight indication in the diffractogram of the untreated sample 917 (Plate 4) of a series of reflections at 8, 12, and 24 Å, which might be a vermiculite/illite mixed-layer.

MONTMORILLONITE. Identified from a basal reflection at 15.4 Å, shifting to 17 Å upon glycolation. Heating to 300°C caused a drop to about 10 Å, which results in a very high illite peak. After heating to 700°C the 10 Å peak again shrank and became slightly broader; sometimes the peak doubled to about 10.0 and 9.8 Å. This also accounts for the (002) and (003) illite peaks. Some of the diagrams showed a small peak at 12.4 Å but this peak was not found after treatment with ethylene glycol.

Quartz. An occasional small peak at 4.27 Å is ascribed to the (100) reflection of quartz-traces.

SEPTECHLORITE. This mineral was identified from its (001) and (002) reflections at 7.07 and 3.53 Å respectively, generally present as a shoulder on the kaolinite peaks but sometimes even projecting above these peaks. Biscaye (1964) recommended inspection of these double peaks to distinguish kaolinite from chlorite. However, the basal reflection of chlorite at 14 Å, which should intensify at 550°C, was not found. Brown (1961) describes a barely perceptible reflection at 14 Å combined with distinct (002) and (003) peaks as characteristic for iron-rich chlorite. But in our diffractograms made after heating to 550°C this 7 Å mineral had disappeared (together with kaolinite), and classification as septechlorite therefore seems more appropriate.

VERMICULITE was identified from a basal reflection at 14.4 Å (cf. Bisdom 1967b), which does not shift upon glycolation, and by the (008) reflection which appears as a shoulder at the right side of the (002) kaolinite peak. The (004) and (006) peaks of vermiculite are of minor intensity but become more important after heating. Heat-treatment affects vermiculite in the same way as it does montmorillonite; the best separation is found at 700°C, where particularly the (003) illite peak and the (006) vermiculite peak bifurcate.

X-ray diffractograms

Technical data on the performance of the X-ray diffraction analysis are given in the legend of Plate 4. Not all of the 26 diffractograms shown on this Plate were originally recorded with the same multiplication factor; therefore, the vertical scale of some of them had to be reduced for presentation in a form comparable to the ones in the same vertical row. Because this cannot be done without loss of detail, the six diffractograms concerned are drawn with a dashed line. Diffraction analysis was performed on two river samples (917, abandoned channel of the Sar River; 915, Ulla River), three samples from the bottom of the ria (59, 605, 456), one sample from the ocean bottom (901)*, and five samples from the deep boring at station 706 (for positions, see Fig. 23). The diffractograms of the untreated clay fractions of these samples are found on the left in Plate 4; samples 706.1 to 706.5 represent the sediment at 3, 5, 7, 9, and 10½ m, respectively. Separate oriented specimens of samples 915, 456, and 706.2 were glycolated and heat treated (at 300, 550, and 700°C); these diffractograms are also shown in Plate 4. For glycolation the slides were held in the vapour of ethylene glycol at 80°C for one hour (cf. Porrenga 1967, p. 17). Specimens of the other samples were also glycol-treated, but the corresponding diffractograms are not shown (with the single exception of 917, in Fig. 22).

The properties of the clay minerals summarized in the preceding section, combined with the data given in Fig. 22, supply the means for a qualitative interpretation of the diffractograms in Plate 4. Confusion of vermiculite with chloritic matter and the approximate coincidence of septechlorite and vermiculite peaks with those of kaolinite (the separate peaks are generally not visible as a result of the unavoidable reduction of the diffractograms) most probably ex-

* The diffractogram of 901 shows three sharp peaks (at 5.95, 2.97, and 1.98 Å) corresponding to basal reflections of whewellite, a Ca-oxalate. Presumably, the clay fraction was erroneously pre-treated with oxalic acid instead of acetic acid.

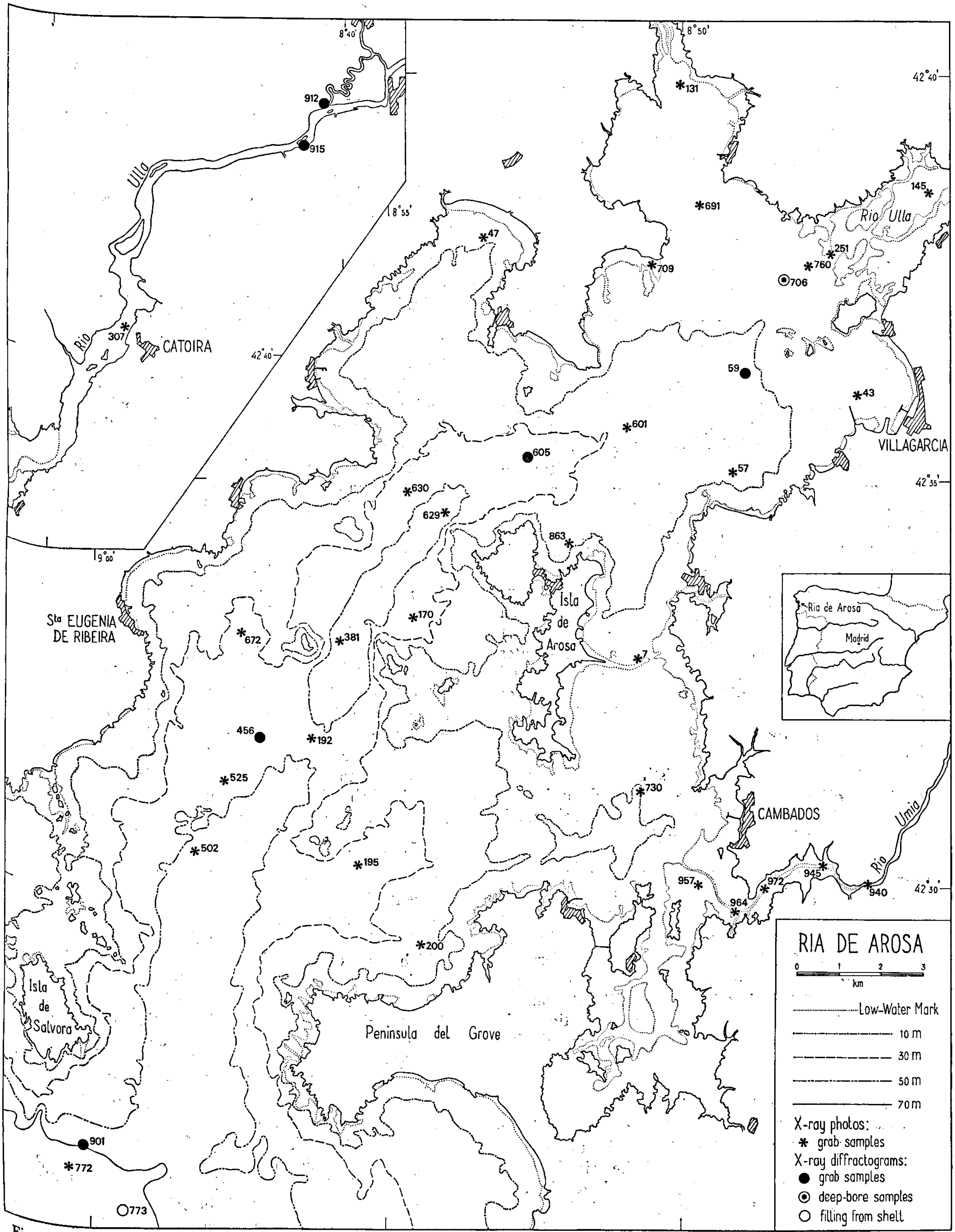


Fig. 23. Location of samples analyzed by X-ray diffractometry (912 should read 917).

plain the discrepancy between the data resulting from the two methods of X-ray analysis.
The latter coincidence also prevents a more or less reliable semi-quantitative interpretation in the form of percentage numbers, but the obvious presence or absence of peaks of certain clay minerals and cautious evaluation of the relative peak-heights for the separate minerals provide a sound basis for an interpretation of the diffractograms.
Kaolinite and illite are the main components of the clay fractions of all samples. Estimation of the ratio kaolinite/illite is rather difficult, because of the presence of other minerals influencing the peak of kaolinite (see above). Nevertheless, we may infer from the diffractograms of untreated and heat treated samples that kaolinite decreases slightly in the direction of the Atlantic Ocean, whereas illite increases. Septechlorite is present in all samples.
Gibbsite is present in the fluviatile samples and in sample 59 as well. Its (002) peak can hardly be distinguished in the diffractogram of sample 605 and is no longer found in the remaining two bottom samples. A similar trend is shown by vermiculite; the sharp (002) peak of this mineral in Fig. 22 marks its importance in the fluviatile muds. The height of this peak is already very low in specimen 59. A trace of vermiculite is still found at number 456, but it is absent in the last diffractogram.
Appreciable amounts of mixed-layer clay minerals are only present at station 917; the unchanged pattern between 10 and 14 Å in the glycolated sample (Fig. 22) with respect to the untreated one in Plate 4 indicates that these mixed-layers are non-expandable. A raised base-line is also clearly visible in the diffractogram of 915, but in the bottom samples of the ria mixed-layers are an unimportant constituent.
The presence of montmorillonite in samples 605, 456, and 901 is demonstrated by a distinct broad peak at 17 Å in the diffractograms of the glycolated specimens; a trace can be detected in sample 59. The mineral is definitely absent in the river samples.
The general aspect of diffractogram 706.1 (sample taken at 3 m sediment depth at station 706) is similar to that of diffractogram 59. Changes in composition with greater depth at this station are irregular (e.g. the (001) and (003) illite peaks of the different diffractograms). Qualitatively, there are no differences between the five samples. Traces of montmorillonite are found at 15.4 Å, but in all the diffractograms a small peak is also present at 12.4 Å; as mentioned in the preceding section, this last peak disappeared after the glycol treatment.

Clay-mineral transport and deposition

The results given in the preceding section provide a more reliable basis for a discussion of the provenance of the clay fraction of the muds of the Ria de Arosa than the data obtained from the X-ray photos, because the diffractograms included untreated and glycol- and heat-treated specimens as well and because minerals of the 7 Å group could be differentiated more successfully. The apparent abundance of kaolinite in the fluvial deposits as compared to the ria-muds suggested by the X-ray photos may not hold true, at least for the Ulla River. No diffractograms were made of samples from the Umia River; but since this river flows through an area in which kaolin deposits are present (Nonn 1966, p. 325), the kaolinite content of its clays may well be even higher.
However, kaolinite and illite are found in all environments, and directions of supply cannot be deduced from their presence. For this purpose the other minerals are more interesting, particularly those showing a distinct trend. Summarizing the results of the preceding section we see that gibbsite, vermiculite, and mixed-layers (all derived from weathering profiles in the Ria de Arosa area), are all important in the river muds but decrease in the ria in the direction of the ocean, gibbsite being the first to disappear. In the opposite direction, montmorillonite is found far into the inner part of the ria. According to Bakker (1963), there is a general marine current along the Galician coast running from north to south, and it seems likely that montmorillonite derives from Western European regions situated more to the north. Montmorillonite can remain in suspension in the waters over the shelf for years (Murray & Harrison 1956).

These trends represent additional evidence of the low transport capacity of the Ulla River. Presumably, even the muds of the inner part of the ria are partially composed of clay coming from the Atlantic as demonstrated by the presence of montmorillonite. We may assume, however, that just before final sedimentation the final direction of transport of some kaolinite and illite is also into the ria. Most clay floccules (or coacervates: Whitehouse *et al.* 1960) do not immediately settle when they are carried in suspension from the estuary of the river into the ria; if they have not sunk into the bottom current before reaching the mouth of the ria, they are carried out into the ocean. During their long journey downwards into deeper water layers they become part of the clay-mineral association in the ocean, and at some moment are carried inward along the ria again by the bottom current (Guilcher 1963). Most of the clay then settles in the outer part of the ria, but a certain amount reaches the inner part. Floccules of montmorillonite, which settles so much more slowly than illite and kaolinite (Whitehouse *et al.* 1960, Porrenga 1966 & 1967), reach the shallowest locations. Effects of differential flocculation and sedimentation are not clearly evident in this area, however, due to the different possible sources of the clay minerals and to seasonal hydrological variations. The latter variations can also be seen as the cause of the variations within sample 706 (cf. Weaver 1959).
Guilcher (1967) lists the rias of Pontevedra and Vigo as typical examples of estuaries filled by river-supplied material. The inner part of these rias is much shallower and narrower than that of the Ria de Arosa; the bay of San Simón (innermost part of the Ria de Vigo) is even semi-enclosed. From a clay-mineralogical point

of view, the filling of the Ria de Arosa has a complex character, because the clay-sized material derives from the upstream part of the principle rivers, the slope deposits near the coast, and the Atlantic Ocean. Similar conditions can also prevail in small rias, as for example in the Ria de San Vicente (Hernández-Pachéco & Asensio Amor 1966). The close connection between topographical and marine conditions, in particular the shape of the bay and the circulation pattern of the water, therefore has a stronger influence on the composition of the muds than does the dimension of the ria.

Glauconite

Llarena & Mateos (1952) found glauconite to be generally present at depths of more than 150 m along the Galician coast. According to Slabaugh & Stump (1964), the depth range of glauconite is 100 to 1200 m, and other publications mention the occurrence of the mineral in shallower zones (Cloud 1955, Burst 1958). The upper limit seems to be related to the geographical latitude; Porrenga (1967, p. 98) mentions that the formation of glauconite is likely to be favoured by temperatures below 15°C.

Other favourable conditions, such as sufficient Fe and K (Burst 1958) and the presence of degraded illitic and/or montmorillonitic material (Triplehorn 1966), also exist in the Ria de Arosa. During part of the year, however, the temperature of the water, even at depths of more than 60 m, is sometimes higher than 15°C; this may explain the absence of glauconite in the bottom sediments of the ria.

Glauconite was found in one sample taken just outside the mouth of the ria. A diffractogram of the filling from a shell found in bottom sample 773 (water depth 82 m) shows the presence of glauconite by a distinct (060) peak at 1.52 Å. This diffractogram, which is not shown here, is in every way identical to the diffractogram of a well-crystallized Paleocene glauconite from New Jersey presented by Porrenga (1967, Fig. 35).

CHAPTER IX

DISCUSSION AND CONCLUSIONS

GENERAL REMARKS

1. The term ria represents a geomorphological concept. The sedimentary processes that play a role in rias resemble those found in other bays, and therefore the sedimentary pattern encountered in the Ria de Arosa does not show specific characteristics distinct from those in other types of bays of similar shape.

2. The Ria de Arosa exhibits an entirely marine environment with an estuarine circulation. The influx of fresh water is only occasionally important during brief periods in the winter; during most of the year tidal and slow wind-driven currents predominate.

3. The Ria de Arosa stretches 25 km inland and has a wide, deep entrance toward the Atlantic Ocean. In accordance with this shape and the low discharge of the confluent rivers, the predominant types of sediment in the Ria de Arosa are muds and sandy muds containing about 90% silt plus clay.

4. Coarse sediments are encountered in the river beds, along the coasts, and in other shallow areas. Their textural properties are principally influenced by the complex local topography.

BIOCLASTS

1. Bioclasts were classified according to two categories: lithothamnion rudite and shell debris. The former is composed of two species of calcareous algae: *Lithothamnion calcareum,* which attaches to the bottom (rock or coarse sediment), and *L. corrallinoides,* which grows loose on all types of sediment. Both species are found mainly as coarse-grained, branched fragments. The shell debris was not differentiated; the grain-sizes range from pebbly sand (whole shells) to very fine sand.

2. Lithothamnion rudite is found in coastal zones, but only where the organisms live at the moment. The inner part of the ria lacks calcareous algae as a result of several unfavourable factors: soft substratum (liquid muds), low oxygen content of the bottom water, and occasional lowering of the pH (influx of fresh water). In the central and outer ria, accumulations of lithothamnion rudite locally comprise the entire sediment. Vertically, growth of lithothamnion rudite extends from the low-water line to a depth of about 10 m at locations near the inner ria; in the direction to the ocean the latter limit gradually becomes deeper and finally reaches about 30 m. Transport of loose branches to deeper zones does not take place.

3. Shell debris is found throughout the ria and accounts for the entire carbonate content of the sediments in deeper waters. This content increases from 5% in the innermost part to about 50% near the mouth of the ria. Accumulations in shallow waters along the coast may contain up to 90% of carbonate matter in areas several hundred metres long. Granular parameters of a zone of shell debris in the ocean just outside the ria suggest that this zone represents a relict sediment. Some accumulations in the ria display similar characteristics.

COARSE NON-CARBONATE SEDIMENTS

1. The provenance and depositional history of the coarse-grained sediments and of the sandy particles in muddy sediments were principally traced from

granulometric data and heavy-mineral studies. Additional information was obtained from roundness estimations of quartz grains and quartz/feldspar ratios. The grain-size distributions are characterized by moment measures. Eight petrographically different areas are distinguished as heavy-mineral associations.

2. Samples from two rivers, the Ulla and the Umia, were investigated. The deposits in the estuaries of both rivers do not agree with their present low discharge. This is demonstrated in the Ulla River particularly by its heavy-mineral association, which must partially derive from rock types in the upstream hinterland. The influence of the Ulla River on the inner part of the ria is mainly restricted to the transport of mud, which extends far into the estuary; samples from this area contained insufficient material for heavy-mineral counts. The estuary of the Umia is covered with pebbly sands; this river enters the ria in a deeper depression. Occasional sandy particles transported into the ria by the Umia River can be traced over a long distance because they include some heavy minerals characteristic of the Umia association (dark hornblende and titanaugite), which differs very distinctly from the surrounding Arosa association.

3. The low quartz/feldspar ratios reflect the mainly granitic origin of the sandy sediments in the coastal areas. Extensive parts of the granites supply very few heavy minerals, and most associations are therefore characterized by metamorphic minerals. Both gradual and abrupt changes in the predominant type of metamorphic rock on the mainland are directly reflected in these heavy-mineral associations; long-shore currents appear to be insignificant. The origin of one association could not be determined; this was the Arosa association, a metamorphic association characterized by kyanite and surrounded by an intrusive granite poor in heavy minerals.

4. A general trend in the grain-size parameters of these sediments was not found. Skewness and degree of sorting are highly dependent on the strength and direction of the water currents, which in their turn are determined by the local topography. The values of moment measures are therefore discussed for the individual places and on the basis of local conditions.

FINE NON-CARBONATE SEDIMENTS

1. Mud of uniform textural composition is deposited everywhere in the deeper waters of the ria. These muds consist of approximately equal amounts of silt and clay, and the mean grain-size fluctuates around 2 microns. The decreasing influence of wave action toward the inner part of the ria is marked by the deposition of mud in shallower areas in this inner part than in the central and outer parts. Sandy muds are found in the outer part of the ria, where the mud is mixed with fine sandy particles occasionally brought in by the bottom current (bimodal sediments).

2. Physical differences are caused by a decrease occurring in the oxygen content of the bottom current as it advances into the inner part of the ria, the low current velocities near the bottom in this area, and the amount of organic matter. Reducing conditions prevail in the black liquid muds of the inner part of the ria; the H_2S smell rapidly disappears toward the outer ria, and the muds become gradually firmer and take on a greenish-grey colour. Hydrotroilite may be responsible for the black appearance of the liquid muds.

3. The clay mineralogy was studied by X-ray diffractometry. The information obtained from photographs made with a Guinier — de Wolff camera was partially misleading, because of similar d-spacings of different minerals whose reflections could not be resolved. Better results were obtained from diffractograms (CuKα-irradiation) of oriented slides of the clay fraction. The Ulla River carries kaolinite, illite, gibbsite, vermiculite, and septechlorite into the ria. Appreciable amounts of mixed-layers are only found in the fluviatile deposits. Kaolinite and illite are common minerals throughout the ria. Gibbsite, vermiculite, and septechlorite decrease in the direction of the ocean; the former mineral is only present in the inner part of the ria. The bottom current transports clay in the opposite direction; terrestrial kaolinite and illite again are the main constituents. The far-reaching influence of this current is shown by the presence of montmorillonite in the inner part of the ria.

SAMENVATTING

De Ria de Arosa, de grootste der zg. klassieke rias in W-Galicië, met een lengte van 25 km en een maximale diepte van meer dan 65 m, vormt het terrein van deze studie. De bodem van de ria vertoont een complexe topografie. De grote verscheidenheid in typen gesteenten, die de ria omgeven, leveren een gevariëerd zware mineralen en kleimineralen-gezelschap.

Dit proefschrift omvat de beschrijving van de verschillende sediment-typen die in deze baai worden aangetroffen. Deze studie is in de eerste plaats gebaseerd op laboratorium-analyses van ongeveer 400 happer-monsters; tevens zijn gegevens verwerkt die verkregen zijn met een punch-corer en met een boor. Uit de resultaten van texturele en petrografische analyses, gecombineerd met de oceanografische en biologische aspecten van de baai, zijn de thans optredende sedimentologische processen afgeleid.

De aangetroffen bioklasten zijn van tweeërlei aard: kalkwier en schelpgruis. Opeenhopingen van *Lithothamnion* (twee soorten) zijn beperkt tot ondiepe gedeelten, waar ze het enige sediment kunnen vormen. Kalkwier ontbreekt in het binnenste deel van de ria;

de ondergrens van hun vertikale uitbreiding daalt in de richting van de Atlantische Oceaan. Schelpgruis is overal in de ria aanwezig en zijn aandeel in het totale sediment neemt toe in dezelfde richting. Opeenhopingen van schelpgruis worden eveneens in de ondiepe gedeelten aangetroffen.
De matige sortering en de afwezigheid van een duidelijk hoofdbestanddeel in de zware mineralen-associatie van de monsters, die genomen zijn uit de bedding van de grootste rivier welke in de ria uitstroomt, de Ulla, wijzen erop dat dit rivier-sediment niet in overeenstemming is met zijn huidige milieu. Hetzelfde geldt voor de grindhoudende zanden van de Umia, de op één na belangrijkste rivier die in de ria uitmondt. De rivieren transporteren slechts zelden zanddeeltjes tot in de ria.
Grofkorrelige sedimenten worden voorts hoofdzakelijk langs de kusten aangetroffen en zijn afkomstig van het lokale vaste gesteente. De grenzen van de verspreidingsgebieden van de acht zware mineralen-associaties, die in de Ria de Arosa zijn onderscheiden, sluiten aan bij de lokale petrologische verschillen op het vasteland. Dit wijst op de geringe betekenis van stromingen evenwijdig aan de kust. Eén metamorfe associatie vormt een uitzondering omdat deze geheel omgeven is door een intrusieve graniet. De herkomst van dit voor de oostkust gelegen sediment (mogelijk een relikt-afzetting) kon niet afdoende verklaard worden. De mate van afronding en de kwarts-veldspaat verhouding bevestigen de onrijpheid van de zandige sedimenten.
Modder en zandige modder zijn de belangrijkste typen sediment op de bodem van de Ria de Arosa. Zwarte, waterrijke modder met een sterke H_2S-geur wordt in het binnenste deel van de ria aangetroffen. Groenig grijze, stevige modder zonder geur komt voor in de centrale en buitenste delen. Deze fysische verschillen zijn het gevolg van de afname van het zuurstofgehalte en van de stroomsnelheid van het water dat over de bodem de ria instroomt.
Dit circulatie-patroon van het water regelt ook de verspreiding van de kleimineralen. De modder is eensdeels afkomstig van de rivieren, die kaoliniet, illiet, gibbsiet en andere mineralen aanvoeren. Mariene klei, eveneens met kaoliniet en illiet als hoofdbestanddelen maar gekarakteriseerd door montmorilloniet, wordt door bodemstromen de ria ingebracht.

RÉSUMÉ

Le sujet de cette étude, la Ria de Arosa, est la plus grande des rias 'classiques' de la Galice occidentale, avec une longueur de 25 km et une profondeur maxima de plus de 65 m. La topographie du fond est assez complexe. La diversité des roches entourant la ria entraîne une grande variété dans la composition des minéraux lourds et des minéraux argileux.
La présente étude donne une description des types de sédiment qu'on trouve dans cette baie. L'étude se base surtout sur les analyses faites au laboratoire sur environ 400 échantillons prélevés au fond, ainsi que sur un certain nombre de carottes. Les processus sédimentaires actuels ont été déduits des propriétés texturelles et pétrographiques des sédiments, ainsi que des conditions océanographiques et biologiques régnant dans la ria.
Les sédiments bioclastiques sont de deux types: l'un, composé d'algues calcaires (maërl), l'autre de débris de coquilles. Les accumulations de *Lithothamnion* (deux espèces) se trouvent seulement dans les parties peu profondes, où parfois elles constituent la totalité du sédiment. Les algues calcaires manquent dans la partie intérieure de la ria; leur limite inférieure descend dans la direction de l'Atlantique. Le débris coquiller est présent partout et son pourcentage augmente dans la même direction. On trouve des accumulations de débris coquiller, comme celles de maërl, dans les parties peu profondes.
Le classement médiocre et l'absence d'un composant dominant dans l'association de minéraux lourds des échantillons pris dans le lit de l'Ulla, la rivière principale débouchant dans la ria, indiquent que le sédiment de cette rivière ne se trouve pas en équilibre avec les conditions actuelles. La même conclusion s'applique aux sables graveleux de l'Umia, la seconde rivière qui se déverse dans la ria. Il est rare que ces rivières apportent des grains de sable jusque dans la ria.
Les sédiments grossiers se trouvent principalement le long des côtes; ils sont dérivés des roches avoisinantes. Aussi les limites des aires occupées par les huit associations de minéraux lourds qu'on a pu distinguer dans la ria correspondent à peu près aux limites entre les roches de la terre ferme. Ce fait prouve la faiblesse des courants le long de la côte. Une association de minéraux métamorphiques constitue une exception, puisqu'elle est entourée par du granite intrusif. Sa provenance est restée incertaine; peut-être dérive-t-elle d'un sédiment ancien.
L'indice d'émoussé peu élevé et la proportion quartz/feldspath confirment l'immaturité des sédiments sableux.
La vase et la vase sableuse sont les types de sédiment les plus répandus sur le fond de la Ria de Arosa. La partie intérieure de la ria se caractérise par une vase noire, riche en eau et sentant le H_2S, tandis que dans les parties centrale et extérieure la vase est plus ferme, de couleur vert-gris, sans odeur. Ces différences sont dûes à la décroissance de la teneur en oxygène et de la vitesse du lent courant de fond qui se dirige vers l'intérieur de la ria.
La même circulation détermine également la distri-

bution des minéraux argileux. D'une part la vase dérive des rivières qui apportent de la kaolinite, de l'illite, de la gibbsite et d'autres minéraux argileux. D'autre part une argile marine, également constituée en majeure partie par de la kaolinite et de l'illite, mais contenant de la montmorillonite, est introduite dans la ria par des courants de fond.

SUMARIO

El objeto de este estudio es la Ría de Arosa, la mas grande de las rías 'clásicas' de Galicia Occidental, con una longitud de 25 km y una profundidad máxima que sobrepasa los 65 m. El fondo de la ría presenta una topografía compleja. La gran variedad de tipos de rocas que rodean la ría suministran minerales pesados y minerales arcillosos de composición variada. La descripción en esta tesis abarca diferentes tipos de sedimentos que ocurren en la bahía. Este estudio está basado en primer lugar en análisis de laboratorio de unas 400 muestras obtenidas con una dragadora; asimismo han sido recogidos datos mediante taladros y perforaciones. Los actuales procesos sedimentarios han sido deducidos de los resultados de análisis texturales y petrográficos, en combinación con las características oceanográficas y biológicas de la bahía.

Dos tipos de bioclásticos han sido distinguido: algas calizas y escombros de conchas. Las acumulaciones de *Lithothamnion* (dos especies diferentes) se limitan a zonas poco profundas, en donde pueden llegar a constituir el único sedimento. Las algas calizas faltan en la parte interior de la ría; el límite inferior de su extensión vertical disminuye en dirección del Oceano Atlántico. Los escombros de conchas están presentes en toda la ría y la cantidad aumenta en la misma dirección. Estos escombros son asimismo encontrados en zonas no profundas.

El moderado surtido y la ausencia de especies dominantes en la asociación de minerales pesados de las muestras tomadas del lecho del río mas grande que desemboca en la ría, el río Ulla, indican que estos sedimentos no están en equilibrio con su actual ambiente. Lo mismo corresponde a las arenas guijarrosas del río Umia, segundo en importancia de los confluentes de la ría. Los ríos solo de vez en cuando suministran partículas de arena a la ría.

Los sedimentos de grano grueso son encontrados principalmente a lo largo de la costa, y proceden de la roca sólida local. Los límites de distribución de las ocho associaciones de minerales pesados, distinguidos en la Ría de Arosa, reflejan las diferencias petrológicas locales en el continente. Esto indica la poca importancia de las corrientes paralelos a la costa. Una asociación metamórfica forma una excepción, porque está completamente rodeada por un granito intrusivo. El origen de este sedimento, situado delante de la costa oriental (posiblemente un sedimento relicto), permanece siendo un problema. La inmadurez de los sedimentos arenosos es confirmado por la redondez y el cociente de cuarzo y feldespato.

Los tipos mas importantes de sedimentos en el fondo de la Ría de Arosa son fango y fango arenoso. Este primero es negro, líquido, con un fuerte olor a H_2S, y se encuentra en la parte interior de la ría. En las zonas central y exterior se halla fango gris verdoso, de constitución firme, e inodoro. Estas diferencias físicas son causados por la disminución del contenido de oxígeno y la disminución de la velocidad de la corriente de fondo que pasa por la ría.

Este tipo de circulación del agua rige también la distribución de minerales arcillosos. El fango es parcialmente suministrado por los ríos, que acarrean kaolinita, ilita, gibbsita y otros minerales. La arcilla marina comprende principalmente kaolinita e ilita, y se caracteriza por montmorillonita, y ha sido introducida en la ría por corrientes de fondo.

REFERENCES

Andel, Tj. H. van, 1950. Provenance, transport and deposition of Rhine sediments. Thesis Wageningen. Veenman, Wageningen: 129 pp. (especially 45).

—, 1959. Reflections on the interpretation of heavy mineral analyses. J. Sed. Petrol., 29: 153—163.

—, 1964. Recent marine sediments of the Gulf of California. In: Marine Geology of the Gulf of California, Symp. Am. Ass. Petr. Geol.: 216—310 (especially 229, 268, 289).

Ardré, F., Cabañas Ruesgas, F., Fischer-Piette, E. & Seaone, J., 1958. Petite contribution à une monographie bionomique de la Ria de Vigo. Bull. Inst. Océanogr. Monaco, 1127: 56 pp.

Arps, C. E. S., 1965. Geomorfologie en sedimentpetrografie van het gebied tussen de mondingen van de Rio Tambre en de Rio Ulla (Provincie Coruña, NW Spanje). Unpublished report.

— & Kluyver, H. M., 1968. Sedimentological investigations on the north-western shores of the Ria de Arosa (NW Spain). Leidse Geol. Meded., 37: (in press).

Asensio Amor, I., 1966. Sedimentología litoral: Los cordones playeros del Golfo de la Masma (Lugo). Bol. R. Soc. Esp. Hist. Nat. (Geol.), 64: 89—112.

Atlas der Bodenbeschaffenheit des Meeres, die Atlantischen Küsten, 1943. Hamburg.

Atlas, Nuevo — de España, 1961. Aguilar, Madrid.

Bakker, J. P., 1963. Grossregionale Verwitterungszonen und Ferntransport von Ton durch Meeresströmungen. Tijdschr. Kon. Ned. Aardr. Genootsch., 80: 109—120.

Behr, S. H., 1965. Heavy mineral beach deposits in the Karroo System. Geol. Surv. South Africa Memoirs, 56: 116 pp.

Berner, R. A., 1967. Diagenesis of iron sulfide in recent marine sediments. In: Lauff, G. H. (ed.), Estuaries; Publ. No. 83 Am. Ass. Adv. Sc., Washington: 268—272.

Berthois, L., 1955. Contribution à l'étude de la sédimentation et de la géologie sous-marine dans le Golfe de Gascogne. Rev. Trav. Inst. Pêches Marit., 19 (4): 501—579.

—, 1965. Recherches sur le comportement hydraulique des débris organogènes. Sedimentology, 5: 327—342.

— & Berthois, C., 1955. Relations entre la granulométrie et le poids des grains de quartz entre 0,063 et 23 mm. Bull. Soc. Géol. France, (6) V: 291—294.

— & Calvez, Y. le, 1961. Étude dynamique de la sédimentation dans la Baie de Sangaréa (Rép. de Guinée). Cah. Océanogr., 13: 694—714.

— & Gendre, A., 1967. Recherches sur le comportement hydraulique des particules sédimentaires. Cah. Océanogr., 19: 95—123.

— & Guilcher, A., 1959. Les bancs de Saint Marc et du Moulin Blanc (Rade de Brest) et remarques sur la sédimentation du Maërl (Lithothamnion calcareum). Cah. Océanogr., 11: 13—23.

Biggs, R. B., 1967. The sediments of Chesapeake Bay. In: Lauff, G. H. (ed.), Estuaries; Publ. No. 83 Am. Ass. Adv. Sc., Washington: 239—260.

Birot, P. & Solé Sabaris, L., 1954. Recherches morphologiques dans le NO de la Péninsule Ibérique. Centre Nat. Rech. Sc., Centre Docum. Cartogr. Géogr., Mém. Docum., 4: 12—61.

Biscaye, P. E., 1964. Distinction between kaolinite and chlorite in recent sediments by X-ray diffraction. Am. Mineralogist, 49: 1281—1289.

—, 1965. Mineralogy and sedimentation of Recent deep-sea clay in the Atlantic Ocean and adjacent seas and oceans. Geol. Soc. Am. Bull., 76: 803—832.

Bisdom, E. B. A., 1965. Verwering, bodems en rivier-sedimenten in de Caldas-graniet. Unpublished report.

—, 1967a. The role of micro-crack systems in the spheroidal weathering of an intrusive granite in Galicia (NW-Spain). Geol. & Mijnbouw, 46: 333—340.

—, 1967b. Micromorphology of a weathered granite near the Ria de Arosa (NW Spain). Thesis Leiden. Leidse Geol. Meded., 37: 33—67.

Bisdom-Dedert, E. H., 1966. Geomorfologie en sedimentpetrografie van het schiereiland El Grove en het eiland La Toja (Galicië, NW-Spanje). Unpublished report.

Blankenburg, H. J. & Jagusch, K. H., 1964. Mögliche Fehler bei Schwermineraluntersuchungen. Zeitschr. Angewandte Geol., 10: 640—650.

Boysse, Ph., 1966. Recherches du B. R. G. M. sur le plateau continental. A—Résultats généraux obtenus par les deux premières campagnes du 'Béluga' en Baie de la Vilaine et ses abords. Bull. Bur. Tech. Géol. Minières, 5: 3—17.

Brajnikov, B., 1944. Sur l'importance de la granulométrie pour l'étude quantitative des minéraux lourds dans un sédiment. Bull. Soc. Géol. France, (5) XIV: 381—390.

Briggs, L. I., 1965. Heavy mineral correlations and provenances. J. Sed. Petrol., 35: 939—955.

Brindley, G. W., 1966. Discussions and recommendations concerning the nomenclature of clay minerals and related phyllosilicates. Proc. 14th Nat. Conf. Clays & Clay Minerals, Pergamon Press, London: 27—34.

Brongersma, L. D. & Pannekoek, A. J., 1966. Investigations in and around the Ria de Arosa, North-West Spain, 1962—1964. Leidse Geol. Meded., 37: 1—5.

Brongersma-Sanders, M., 1965. Metals of Kupferschiefer supplied by normal sea water. Geol. Rundschau, 55: 365—375.

Brown, G., 1961. The X-ray identification and crystal structures of clay minerals. Mineral. Soc. London: 544 pp.

Burst, J. F., 1958. 'Glauconite' pellets: their mineral nature and applications to stratigraphic interpretations. Am. Ass. Petr. Geol. Bull., 42: 310—327.

Cadée, G. C., 1968. Molluscan biocoenoses and thanatocoenoses in the Ria de Arosa, Galicia, Spain. Thesis Leiden. Zoöl. Verh. Rijksmus. Nat. Hist. Leiden, 95: 1—121.

Cadigan, R. A., 1961. Geologic interpretation of grain-size distribution measurements of Colorado Plateau sedimentary rocks. J. Geol., 69: 121—144.

Carlé, W., 1947. Die westgalicischen Meeresbuchten. Natur und Volk, 77: 5—14.

Cloud, P. E., 1955. Physical limits of glauconite formation. Am. Ass. Petr. Geol. Bull., 39: 484—492.

Conaghan, P. J., 1966. Sediments and sedimentary processes in Gladstone Harbour, Queensland. Univ. Queensland Papers, 6: 1—52.

Cotton de Bennetot, M., Guilcher, A. & Saint-Requier, A., 1965. Morphologie et sédimentologie de l'Aber Benoît (Finistère). Cah. Océanogr., 17: 377—387.

Curray, J. R., 1960a. Sediments and history of Holocene transgression, continental shelf, Northwest Gulf of Mexico. In: Recent sediments, Northwest Gulf of Mexico, Am. Ass. Petr. Geol. Symp.: 221—266.

—, 1960b. Tracing sediment masses by grain-size modes. Rept. 21st Session, Norden, Intern. Geol. Congr., Copenhagen: 119—130.

—, 1965. Late Quaternary history, continental shelves of the United States. In: The Quaternary of the United States, Princeton, New Jersey: 723—735.

Díez Taboada, J. M., 1964. Sedimentos costeros arenosos actuales de la Ría de Arosa. Bol. R. Soc. Esp. Hist. Nat. (Geol.), 62: 361—364.

—, 1965. Procesos de accumulación y evolutivo de las fases arenosas actuales de la Ría de Arosa. Bol. R. Soc. Esp. Hist. Nat. (Geol.), 63: 129—135.

Doeglas, D. J., 1940. The importance of heavy mineral analyses for regional sedimentary petrology. Rept. Sed. U.S. Nat. Res. Counc.: 22 pp.

—, 1952. Afzettingsgesteenten. Servire's Encyclopaedie, A 5/6: 173 pp.

Dryden, L. & Dryden, C., 1946. Comparitive rates of weathering of some common heavy minerals. J. Sed. Petrol., 16: 91—96.

Duane, D. B., 1964. Significance of skewness in recent sediments, Western Pamlico Sound, North Carolina. J. Sed. Petrol., 34: 864—874.

Dunbar, C. O. & Rodgers, J., 1957. Principles of Stratigraphy. Wiley & Sons, New York: 356 pp. (especially 75).

Edelman, C. H., 1938. Ergebnisse der sedimentpetrologischen Forschung in den Niederlanden und den angrenzenden Gebieten 1932—1937. Geol. Rundschau, 29: 223—273.

— & Doeglas, D. J., 1933. Bijdrage tot de petrologie van het Nederlandsche Tertiair. Verh. Kon. Geol. Mijnbouwk. Gen., Geol. Ser., 10: 1—38.

Edgerton, H. E. & Payson, H., 1964. Sediment penetration with a short-pulse sonar. J. Sed. Petrol., 34: 876—880.

Emery, K. O., Gorsline, D. S., Uchupi, E. & Terry, R. D., 1957. Sediments of three bays of Baja California: Sebastian Viscaino, San Cristobal and Todos Santos. J. Sed. Petrol., 27: 95—115.

— & Rittenberg, S. C., 1952. Early diagenesis of California basin sediments in relation to origin of oil. Am. Ass. Petr. Geol. Bull., 36: 735—806 (especially 751).

Floor, P., 1968. Basement rocks of western Galicia as sources for the minerals in the Ría de Arosa. Leidse Geol. Meded., 37: 69—76.

Folk, R. L., 1954. The distinction between grain size and

mineral composition in sedimentary-rock nomenclature. J. Geol., 62: 344—359.
—, 1966. A review of grain-size parameters. Sedimentology, 6: 73—93.
Friedman, G. M., 1961. Distinction between dune, beach, and river sands from their textural characteristics. J. Sed. Petrol., 31: 514—529.
—, 1962. On sorting, sorting coefficients, and the lognormality of the grain-size distribution of sandstones. J. Geol., 70: 737—753.
—, 1965. Relationship between statistical parameters derived from size frequency distribution of sands and environment of deposition (abstract). Trans. Am. Geoph. Union, 46: 108.
—, 1966. Moment measures in relation to the depositional environment of sands, a critique. Eclogae Geol. Helv., 59: 773—775.
—, 1967. Dynamic processes and statistical parameters compared for size frequency distribution of beach and river sands. J. Sed. Petrol., 37: 327—354.
Fuller, A. O., 1961. Size distribution characteristics of shallow marine sands from the Cape of Good Hope, South Africa. J. Sed. Petrol., 31: 256—261.
Gaudette, H. E., Eades, J. L. & Grim, R. E., 1966. The nature of illite. Proc. 13th Nat. Conf. Clays & Clay Minerals, Pergamon Press, London: 33—48.
Giresse, P., 1965. Rôle du continent dans la sédimentation fluviatile et cotière de la Province de Barcelona (premières observations). Notas y Comun. Inst. Geol. Minero de España, 80: 71—84.
Gonzalez Peña, J. M. & Perez Mateos, J., 1958. Estudio mineralógico comparativo de la fracción arcilla de algunos sedimentos del litoral español. Apéndice: Mineralogía de la fracción 'arena' de los sedimentos marinos que se estudian. An. Edaf. Fisiol. Vegetal, 17: 27—56.
Graaff, W. P. F. H. de & Woensdregt, C. F., 1963. Heavy mineral analysis of the beaches between Ría de Leres and Ría de Muros y Noya (Prov. La Coruña, NW Spain). Est. Geol., 19: 9—14.
Grant, W. H., 1966. Kaolinite stability in the Central Piedmont of Georgia. Proc. 13th Nat. Conf. Clays & Clay Minerals, Pergamon Press, London: 131—140.
Griffiths, J. C., 1951. Size versus sorting in some Caribbean sediments. J. Geol., 59: 211—243.
—, 1957. Size-frequency distribution of detrital sediments based on sieving and pipette sedimentation (abstract). Geol. Soc. Am. Bull., 68: 1739.
Guilcher, A., 1963. Estuaries, deltas, shelf, slope. In: Hill, M. N. (ed.), The Sea, 3, III: Sedimentation. Wiley & Sons, London: 620—654.
—, 1964. La sédimentation sous-marine dans la partie orientale de la Rade de Brest, Bretagne. Proc. 6th Intern. Sed. Congr., Developments in sedimentology, 1, Elsevier, Amsterdam: 148—156.
—, 1967. Origin of sediments in estuaries. In: Lauff, G. H. (ed.), Estuaries; Publ. No. 83 Am. Ass. Adv. Sc., Washington: 149—157.
— & Pruleau, M., 1963. Morphologie et sédimentologie sous-marines de la partie orientale de la Rade de Brest. Bull. Sect. Géogr. Com. Trav. Hist. Sci., 75: 81—116.
Harten, D. van, 1965. On the estimation of relative grain frequencies in heavy mineral slides. Geol. & Mijnbouw, 44: 357—363.
Hernández-Pachéco, F. & Asensio Amor, I., 1966. Fisiografía y sedimentología de la playa y ría de San Vicente de la Barquera (Santander). Est. Geol., 22 : 1—23.
Hoek, C. van den & Donze, M., 1967. Algal phytogeography of the European Atlantic coasts. Blumea, 15: 63—89.
Hoshino, M., 1964. Rías coasts around Japanese islands (abstract). In: Hidaka, K. (ed.), Studies on Oceanography, Univ. Washington Press: 479—485.
Hower, J. & Mowatt, T. C., 1966. The mineralogy of illites and mixed-layer illite/montmorillonites. Am. Mineralogist, 51: 825—854.
Johnson, J. H., 1962. The algal genus Lithothamnium and its fossil representatives. Quart. Colorado School Mines, 57: 1—111.
Kalsbeek, F., & Zwart, H. J., 1967. Zircons from some gneisses and granites in the Central and Eastern Pyrenees. Geol. & Mijnbouw, 46: 457—466.
Kaplan, I. R. & Rittenberg, S. C., 1963. Basin sedimentation and diagenesis. In: Hill, M. N. (ed.), The Sea, 3, III: Sedimentation. Wiley & Sons, London: 583—619.
Kennedy, J. F. & Koh, R. C. Y., 1961. The relation between the frequency distributions of sieve diameters and the fall velocities of sediment particles. J. Geophys. Res., 66: 4233—4246.
Koldijk, W. S., 1968. On environment-sensitive grain-size parameters. Sedimentology, 10: (in press).
Korringa, P., 1967. Estuarine fisheries in Europe as affected by man's multiple activities. In: Lauff, G. H. (ed.), Estuaries; Publ. No. 83 Am. Ass. Adv. Sc., Washington: 658—663.
Krumbein, W. C., 1934. Size frequency distribution of sediments. J. Sed. Petrol., 4: 65—77.
— & Sloss, L. L., 1963. Stratigraphy and Sedimentation. Freeman, San Francisco (2nd ed.): 660 pp. (especially 124).
Kuenen, P. H., 1959. Sand — its origin, transportation, abrasion, and accumulation. Geol. Soc. South Africa, DuToit Mem. Lect., 6: 33 pp.
Link, A. G., 1966. Textural classification of sediments. Sedimentology, 7: 249—254.
Llarena, J. G. de, 1952. Observaciones sobre los sedimentos de las costas de Galicia. Bol. Inst. Esp. Oceanogr., 52: 32 pp.
McCammon, R. B., 1962. Moment measures and the shape of size frequency distributions. J. Geol., 70: 89—92.
McCrone, A. W., 1966. Sediments from Long Island Sound (New York): Physical and chemical properties reviewed. J. Sed. Petrol., 36: 234—236.
McEwen, M. C., Fessenden, F. W. & Rogers, J. J. W., 1959. Texture and composition of some weathered granites and slightly transported arkosic sands. J. Sed. Petrol., 29: 477—492.
Maps, Old — from the Bodel-Nijenhuis collection, Leiden.
1693. Cartes des costes septentrionales d'Espagne depuis Fontarabie jusqu'à Bayonne en Gallice.
1751. Cartes réduits des Costes d'Espagne et de Portugal depuis le Cap Pinas jusqu'au Détroit de Gibraltar. Dressée par ordre de M. Rouillé.
1793. Côtes d'Espagne, Partie de la Gallice depuis le Cap Ortegal jusqu'au Cap Silleiro d'après les Plans levés en 1787 par Don Vicente Tofiño.
1804. Chart of the Coasts of Spain and Portugal, from Cape Pinas to the Strait of Gibraltar. P. Steel, Little Tower Hill, London.
1823. Carta esterica de las costas de la peninsula de España, las de Francia è Italia hasta el Cabo Venere, y la correspondiente de Africa en esta parte del Mediterraneo. Gaspar Masa. Direccion hidrografica, Madrid.
Masachs Alavedra, V., 1954. El clima. Las aguas. In: Solé Sabaris, L., Geografía de España y Portugal, España, Geografía física, II: 9—142. Montaner y Simón, S. A., Barcelona.
Middleton, G. V., 1962. On sorting, sorting coefficients, and

the lognormality of the grain-size distribution of sandstones: a discussion. J. Geol., 70: 754—756.
Milner, H. B., 1962a. Sedimentary Petrography. Volume I. Methods in Sedimentary Petrography. Allen & Unwin Ltd., London (4th ed.): 645 pp. (especially 113, 158, 174).
—, 1962b. Sedimentary Petrography. Volume II. Principles and Applications. Allen & Unwin Ltd., London (4th ed.): 715 pp.
Mitsushio, H., 1967. Bottom sediments in bays of North Kyushu. Mem. Fac. Sc. Kyushu Univ., Ser. D Geol., 18: 7—34.
Moore, J. R., 1963. Bottom sediments studies, Buzzards Bay, Massachusetts. J. Sed. Petrol., 33: 511—558.
Moss, A. J., 1966. Origin, shaping and significance of quartz sand grains. J. Geol. Soc. Austr., 13: 97—136.
Mrazek, H., 1965. Zur Verteilung der Turmalin-Farbvarietäten unter limnischen Ablagerungsbedingungen. Geologie, 14: 1274—1276.
Müller, G., 1958. Die rezenten Sedimenten im Golf von Neapel. 1. Die Sedimente des Golfes von Pozzuoli. Geol. Rundschau, 47: 117—150.
Murray, H. H. & Harrison, J. L., 1956. Clay mineral composition of recent sediments from Sigsbee Deep. J. Sed. Petrol., 26: 363—368.
Nonn, H., 1964. Los sedimentos antiguos de la Ría de Arosa: algunos conclusiones geomorfológicas. Notas Comun. Inst. Geol. Miner. Esp., 74: 143—156.
—, 1966. Les régions cotières de la Galice (Espagne). Étude géomorphologique. Publ. Fac. Lettres Univ. Strasbourg, III: 591 pp. (especially 37, 63, 325—330).
Orbell, G. E., 1965. Petrology and clay mineralogy of some sedimentary rocks from the Mauriceville District. New Zealand J. Geol. Geophys., 8: 548—559.
Page, H. G., 1955. Phi-millimeter conversion table. J. Sed. Petrol., 25: 285—292.
Pannekoek, A. J., 1966a. The Ria Problem. The rôle of antecedence, deep weathering, and Pleistocene slope-wash in the formation of the West-Galician rias. Tijdschr. Kon. Ned. Aardr. Genootsch., 83: 289—297.
—, 1966b. The geomorphology of the surroundings of the Ria de Arosa (Galicia, NW Spain). Leidse Geol. Meded., 37: 7—32.
Pantin, H. M., 1966. Sedimentation in Hawke Bay. Bull. New Zealand Dept. Sc. Industr. Res., 171: 70 pp. (especially 59).
Parga-Pondal, I., 1935. Arena monacítica de la Ría de Arosa. An. Soc. Esp. Fis. Quim., 33: 466—469.
Pettijohn, F. J., 1957. Sedimentary rocks. Harper & Brothers, New York (2nd ed.): 718 pp. (especially 58—59, 221).
Pilkey, O. H., 1964. The size distribution and mineralogy of the carbonate fraction of United States South Atlantic Shelf and upper slope sediments. Mar. Geol., 2: 121—136.
Poole, D. M., 1958. Heavy mineral variation in San Antonio and Mesquite Bays of the Central Texas Coast. J. Sed. Petrol., 28: 65—74.
Porrenga, D. H., 1966. Clay minerals in Recent sediments of the Nigerdelta. Proc. 14th Nat. Conf. Clays & Clay Minerals, Pergamon Press, London: 221—233.
—, 1967. Clay mineralogy and geochemistry of Recent marine sediments in tropical areas. Thesis Amsterdam. Stolk, Dordrecht: 145 pp. (especially 17, 19, 55, 98, Fig. 35).
Pritchard, D. W., 1967. What is an estuary: Physical viewpoint. In: Lauff, G. H. (ed.), Estuaries; Publ. No. 83 Am. Ass. Adv. Sc., Washington: 3—5.
Pryor, W. A. & Glass, H. D., 1961. Cretaceous-Tertiary clay mineralogy of the Upper Mississippi Embayment. J. Sed. Petrol., 31: 38—51.
Rateyev, M. A., 1963. Modification degree of clay minerals during the stage of sedimentation and diagenesis of marine deposits. Proc. Int. Clay Conf. Stockholm, Pergamon Press, London: 171—180.
Raumer, J. von, 1963. Zur Tektonik und Genese des nordwestspanischen Kernkristallins bei Noya (La Coruña). Geotekt. Forsch., 17: 63 pp.
Richthofen, F. von, 1886. Führer für Forschungsreisende. Oppenheim, Berlin: 730 pp. (especially 308—310).
Rogers, J. J. W., 1959. Detection of lognormal size distributions in clastic sediments. J. Sed. Petrol., 29: 402—407.
Saínz-Amor, E., 1959. Seriación de los minerales pesados en una muestra profunda recogida en Guisar (Ría de Vigo). Est. Geol., 15: 329—333.
—, 1960. Estudio morfoscópico de las arenas de la Ría de Vigo. Est. Geol., 16: 35—42.
—, 1962. Estudio granulométrico de las arenales de la Ría de Vigo. Bol. R. Soc. Esp. Hist. Nat. (Geol.), 60: 77—92.
— & Amorós, J. L., 1962. Composición mineralógica de las arenas de la Ría de Vigo. Bol. R. Soc. Esp. Hist. Nat. (Geol.), 60: 177—194.
Sander, N. J., 1967. Classification of carbonate rocks of marine origin. Am. Ass. Petr. Geol. Bull., 51: 325—336.
Saxena, S. K., 1966. Evolution of zircons in sedimentary and metamorphic rocks. Sedimentology, 6: 1—33.
Schermerhorn, L. J. G., 1966. Terminology of mixed coarse-fine sediments. J. Sed. Petrol., 36: 831—835.
Scheu, E., 1913. Die Rías von Galicien. Ihr Werden und Vergehen. Zeitschr. Ges. Erdk. Berlin: 84—114, 193—210.
Schneider, E. D. & Heezen, B. C., 1966. Sediments of the Caicos Outer Ridge, The Bahamas. Geol. Soc. Am. Bull., 77: 1381—1398.
Schock, R. N., 1965. Note on the texture of some Pleistocene sands. J. Sed. Petrol., 35: 500—503.
Schülke, H., 1967. Organische Strandwälle und Nehrungen in Korsischen Rias. Erdkunde, 21: 1—11.
Sevon, W. D., 1966. Sediment variation on Farewell Spit, New Zealand. New Zealand J. Geol. Geophys., 9: 60—75.
Shepard, F. P., 1954. Nomenclature based on sand-silt-clay ratios. J. Sed. Petrol., 24: 151—158.
Slabaugh, W. H. & Stump, A. D., 1964. Surface areas and porosity of marine sediments. J. Sed. Petrol., 69: 4773—4778.
Stewart, R. A. & Gorslin, D. J., 1962. Recent sedimentary history of St. Josephs Bay, Florida. Sedimentology, 1: 256—286.
Stoch, L., 1961. Titanium in kaolinite clays. Bull. Acad. Polon. Sc., 9: 135—141.
Straaten, L. M. J. U. van, 1965. Sedimentation in the North-Western part of the Adriatic Sea. Butterworth, London; Colston Papers, 17: 143—162.
—, 1966. Micro-malacological investigation of cores from the Southeastern Adriatic Sea. Proc. Kon. Ned. Akad. Wetensch., B, 69: 429—445.
Swanson, H. E., 1950. Tables for the conversion of X-ray diffraction angles to interplanar spacing. U.S. Government Printing Office, Nat. Bur. Standards, Appl. Mathem. Ser., 10: 159 pp.
Swinchatt, J. P., 1965. Significance of constituent composition, texture, and skeletal breakdown in some recent carbonate sediments. J. Sed. Petrol., 35: 71—90.
Triplehorn, D. M., 1966. Morphology, internal structure, and origin of glauconite pellets. Sedimentology, 6: 247—266.
Tröger, W. E., 1959. Optische Bestimmung der gesteinsbildenden Minerale. Teil 1. Bestimmungstabellen. Schweizerbart, Stuttgart (3rd ed.): 147 pp.
Uras, I. & Tamburrini, D., 1966. Applicazioni del calcolatore

elettronico nella determinazione dei parametri caratteristica delle distribuzioni de frequenze granulometriche dei sedimenti. Boll. Soc. Geol. Italia, 85: 59—69.
Vanney, J.—R., 1965. Étude sédimentologique du Mor Bras, Bretagne. Mar. Geol., 3: 195—222.
Venkataratnam, K. & Poornachandra Rao, M., 1965. Studies in grain-size (coarse fraction) and mineral content of marine sediments off Visakhapatnam. Quart. J. Geol. Min. Metall. Soc. India, 37: 101—107.
Vogel, D. E., 1965. Thin sections for determining the composition of the light-mineral fraction of unconsolidated sediments. Geol. & Mijnbouw, 44: 64—65.
Weaver, C. E., 1959. The clay petrology of sediments. Proc. 6th Nat. Conf. Clays & Clay Minerals, Washington: 154—187.
Whitehouse, U. G., Jeffrey, L. M. & Debbrecht, J. D., 1960. Differential settling tendencies of clay minerals in saline waters. Proc. 7th Nat. Conf. Clays & Clay Minerals, Washington: 1—80.
— & McCarter, R. S., 1958. Diagenetic modification of clay mineral types in artificial sea water. Proc. 5th Nat. Conf. Clays & Clay Minerals, Washington: 81—119.
Wolf, K. H., 1961. The flotation phenomenon — a bypassing and sorting process. J. Sed. Petrol., 31: 476—478.
Wood, L. E., 1964. Bottom sediments of Saginaw Bay, Michigan. J. Sed. Petrol., 34: 173—184.
Yañez C., A., 1963. Batimetría, salinidad, temperatura y distribución de los sedimentos recientes de la Laguna de Términos, Campeche, México. Bol. Inst. Geol. Univ. Nac. Aut. Mex., 67: 47 pp.
Yoder, H. S. & Eugster, H. P., 1955. Synthetic and natural muscovites. Geochimica Cosmochimica Acta, 8: 225—280.