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COASTAL SEDIMENTS OF THE SOUTHEASTERN SHORES OF THE RÍA DE AROSA (GALICIA, NW SPAIN)

BY

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ABSTRACT

The beaches of the southeastern shore of the Ría de Arosa are in general small and enclosed between rocky capes; especially those along the inner ria are not subjected to strong wave action. Nonetheless, the beach sands are often coarse-grained, being partially derived from the coarse-grained intrusive granites exposed in low cliffs along the major part of the shore. Generally, the sands along the low-water mark are finer than the better-sorted sands along the high-water mark, since the backwash is not able to transport the coarse grains. In some cases, however, granules derived from weathering granite are left behind at the low-water mark because the waves are too weak to carry them higher up on the beach. In protected embayments tidal flats originated whose sediments are much finer grained than those of the beaches, although they are relatively coarse-grained as compared with tidal-flat sediments in general. At some places there is a supply of pebbles deriving from colluvium and from raised beaches.

The heavy minerals partially reflect the composition of the basement rocks exposed in low cliffs (epidote association, tourmaline association). The hornblende association is supplied by the two main rivers and is found near their mouths, but the hornblende content rapidly decreases due to weathering. The metamorphic association, occupying the largest area, may to some extent have been supplied by colluvium (derived from xenoliths in the granite), but a greater proportion was probably supplied by rivers (Ulla and small rivers on the opposite shore), which deposited sediments on the ria bottom (as shown by seismic profiles), from where it was washed ashore during the late-glacial rise of the sea level.

The quartz/feldspar ratios are highest where the beaches are most exposed.

SUMARIO

Sedimentos litorales del borde suroriental de la Ría de Arosa (Galicia)

Las playas del borde suroriental de la Ría de Arosa son en su mayoría pequeñas y estan encerradas entre cabos rocosos. Las que estan situadas a lo largo de la ría interior no estan expuestas a la fuerte acción de las olas. No obstante, las arenas de las playas son frecuentemente de grano grueso, siendo parcialmente derivadas de granitos intrusivos de grano grueso expuestos en escarpas bajas a lo largo de la mayor parte del borde de la ría. Generalmente, las arenas a lo largo de la línea de marea baja son más finas que las mejor clasificadas a lo largo de la línea de marea alta, debido a que el "backwash" no es capaz de transportar los granos gruesos. En algunos casos, los gránulos derivados de granito alterado son dejados detrás de la línea de marea baja ya que las olas son demasiado débiles para transportarlos a partes más altas de la playa. En bahías protegidas se originaron plataformas de marea en las cuales los sedimentos son de grano más fino que en otras partes, aunque grueso en comparación con los sedimentos de plataforma de marea en general. En algunos casos las playas se suministran de cantos provenientes de coluvio y de terrazas costeras.

Los minerales pesados reflejan parcialmente la composición de las rocas de basamento expuestas en escarpas bajas (asociación de epidota, asociación de turmalina). La asociación de hornblenda es suministrada por los dos ríos principales y se encuentra cerca de sus desembocaduras, pero el contenido de la hornblenda decrece rápidamente a causa de la alteración. La asociación metamórfica, que ocupa el area mas grande, puede ser en parte suministrada por coluvio (derivado de xenolitos en el granito), pero en gran parte ha sido seguramente suministrada por ríos (Ulla y pequeños ríos de la costa opuesta) los cuales depositaron sedimentos en el fondo de la ría (como es demonstrado por perfiles sísmicos), del que fue arrastrado a la playa durante la última elevación del nivel del mar.

Los coeficientes cuarzo/feldespato son mas altos cuanto más expuestas son las playas.

CONTENTS

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INTRODUCTION

Among the graduate students of Leiden University who carried out fieldwork as part of the Ría de Arosa investigation during the summer months of 1962, 1963, and 1964, the junior author of the present article (H.H.P.) worked on the beaches along the left (i.e. southeastern) shore of the ria (Poortman, internal report, 1969), Mrs. Liesbeth Bisdom studied the coastal sediments and the morphology of the El Grove Peninsula (internal report, 1967), Mr. D. J. Wiersma worked in the Ensenada del Grove, the tidal-flat area in the embayment north of the tombolo connecting the El Grove Peninsula with the mainland (internal report, 1967), and Mr. A. L. E. Amstelveen worked on weathering products of basement rocks east of the Ensenada del Grove (internal report, 1965). Their reports provided the data for the present paper, compiled by the senior author who directed and supervised most of their works.

In this paper frequent reference will be made to the papers by C. E. S. Arps & H. M. Kluyver, who described the opposite (northwestern) shore of the ria (this volume, p. 135—145), Dr. W. S. Koldijk, who studied the bottom sediments (this volume, p. 77—134), and Dr. E. B. A. Bisdom, who worked on weathering phenomena in the area adjoining the southeastern shore of the Ría de Arosa (this volume, p. 33—67).

The authors are indebted to Professor A. J. Pannekoek for his critical reading of and comments on the first draft of this paper and to Mr. M. L. Brittijn for his able draughtmanship.

MORPHOLOGY

General features

The boundary between the weakly undulating hinterland, sloping gradually towards the ria, and the inundated part of the ria is formed by an indented coastline. Along this coastline outcrops of intrusive and metamorphic rocks of the basement complex, forming small capes, alternate with sandy beaches (Fig. 1), whereas in some embayments or otherwise protected coastal parts, tidal flats have developed.

The middle section of the coastline is more or less protected by a large island, the Isla de Arosa, consisting of granitic hills connected by tombolos covered by windblown sand. The island shows a girdle of beaches all around, wider along the eastern than along the western shore. Along the W coast some small tidal flats with salt-marsh vegetation have also developed. At the E side, facing the mainland, a cuspate spit has developed (Phot. 1), most probably as a result of the meeting of material driven southward by strong northern winds in summer, and by material driven northward by strong southern winds in winter, although the tides may also contribute to this effect (Díez Taboada, 1967). Numerous small islands, mostly granitic tors, have no beaches and are simply bare rocks washed by the waves of the ria.

Before the outer section of the southeastern ria coast lies the still larger Peninsula del Grove, a former island, now connected with the mainland by the tombolo of La Lanzada. The S coast of this peninsula and the S shore of the tombolo face the Atlantic Ocean and are subjected to stronger wave and wind action than the coasts of the inner ria.

In the large embayment N of the tombolo, the Ensenada del Grove, which is protected on three sides (by the tombolo, the E coast of the peninsula, and the mainland), a tidal-flat area of about 12 square kilometres has developed; this area will be dealt with in a separate section of this paper.

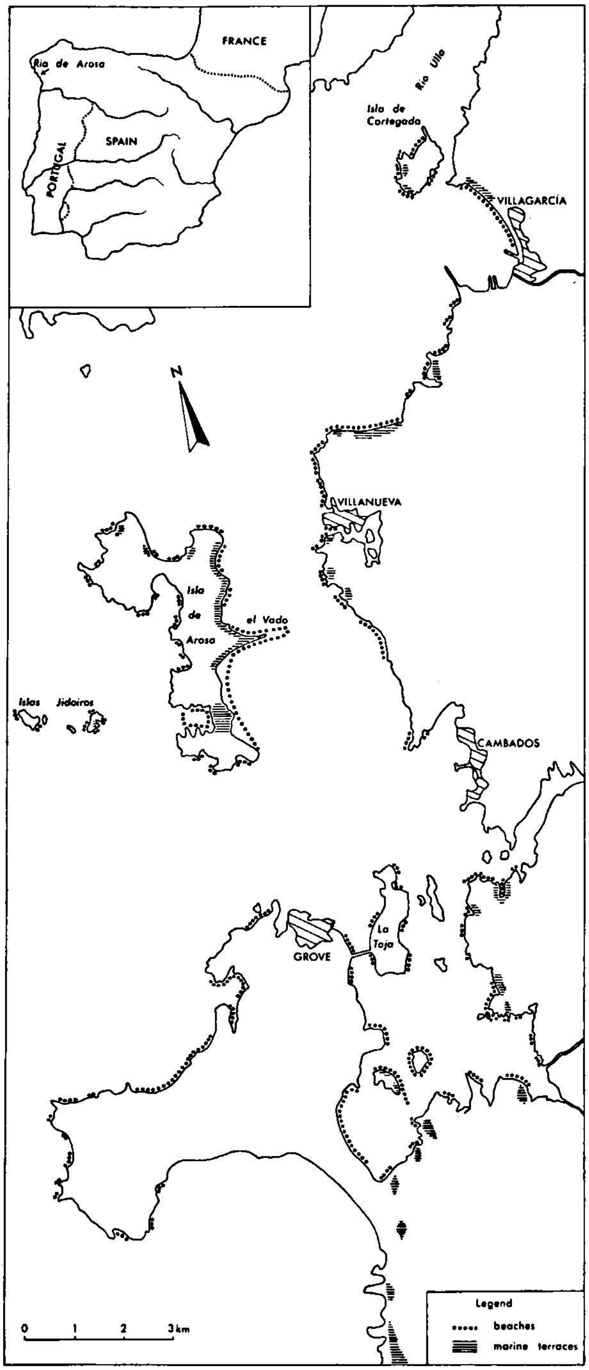


Fig. 1. Distribution of beaches along the southeastern shore of the Ría de Arosa. Approximate scale 1:150,000.

Phot. 1. El Vado cuspate foreland seen towards the Isla de Arosa.

Geology of the hinterland

In contrast to the opposite shore, the SE coast of the ria is situated over nearly its whole length in only one type of rock, the coarse-grained, intrusive, late-hercynian Caldas de Reyes granite (Floor, 1968). Only at the northern end, N of Villagarcía de Arosa, do some other rock-types occur along the coast, i.e. two-mica granites and some gneisses. Other rocks, mostly mica schists, are also found S of the ria, along the open ocean.

The Caldas granite is, however, not homogeneous, and contains numerous schist-like xenoliths. Díez Taboada (1965, 1967) mentions the local occurrence of metamorphic rocks from the Isla de Arosa, which was confirmed by one of us (H.H.P.), but whether these are xenoliths or larger bodies could not be determined.

The beaches

The beaches consist mainly of sand; locally, small concentrations of pebbles are found, but shingle beaches are absent. Most of the beaches are not more than some hundreds of metres long, the longest in this area being the 2 km long beach between Villagarcía and Carril, the Playa de Compostela, and the 3 km long beach of the tombolo of La Lanzada. The width of the beaches hardly ever exceeds 100 m, the average being about 50 m.

Whether or not a beach has developed appears to depend partially on the angle between the most important joint direction in the basement rocks and the coastline: where the joints cut the coastline more or less perpendicularly and loose material is available, arcuate beaches between capes occur; where the angle with the major joints is small, as is the case for part of the coast between Villanueva and Cambados, the shore consists of parallel ridges of bedrock and no beach has developed.

Small tombolos occur where islets of bedrock, mostly granitic tors, are found near the shore in a sandy, shallow area, and where the deposition of sand is not prevented by the occurrence of strong tidal currents.

Beach profiles

The relatively coarse-grained upper parts of the beaches dip about 10° near high-water and spring-tide marks, whereas the dip near the relatively fine-grained low-water mark is generally less than 2°.

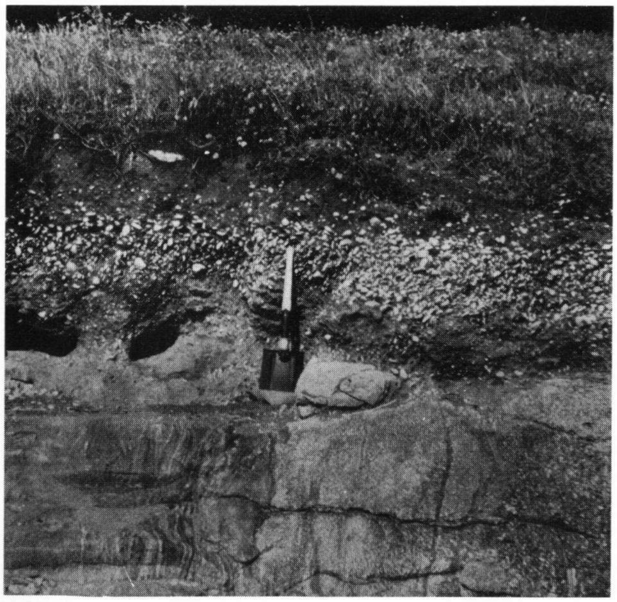
Each high tide between spring tide and neap tide leaves behind a relatively coarse-grained ridge at a somewhat lower level than the preceding one. During the following week, between neap tide and spring tide, when the daily high-water level lies some 15 cm higher each day, the bulk of the newly deposited material is carried landward and is finally deposited on the berm at spring tide.

The tides in the ria follow the calculated cycles closely. Storm floods are not known along the coasts, as shown by the simple fact that houses have been built very near the high-water level and no measures to prevent flooding are taken. Apart from some shallow embayments the ria is relatively deep (more than 50 m in the central channel, less than 30 m in the inner ria) and water driven ashore by the wind has plenty of room to flow back. This also holds for the action of off-shore winds, since upwelling currents can directly compensate for a loss of water.

To study the internal structure of the beaches, ditches about 20—50 cm deep were dug at several places. In these ditches a bedding lying parallel to the surface or dipping seaward at an angle of 5—15° was observed. However, because of intensive digging for shellfish by the local population, the original bedding has been disturbed at many places. At some locations a black humic layer is exposed in the ria beaches, probably representing a soil dating from a time when the sea-level was still below the present one.

Cliffs

In several places the mainland is bounded at the ria side by a low abrasion cliff. Most of the cliffs show strongly weathered intrusive or metamorphic bedrock, whereas occasionally a layer of well-rounded pebbles overlain by head (colluvium) occurs (Phot. 2). Some low cliffs (2—3 m) consist wholly of colluvium with pebbles, derived from Pleistocene beach deposits.



Phot. 2. Ancient pebbly beach deposit, overlain by colluvium, on top of bedrock. Isla de Arosa.

Where cliffs are absent, a berm has usually developed at the spring-tide level; behind the berm there is occasionally a lagoon 20 to 50 m long.

Wind-blown sands occur locally in the coastal area, deriving directly from the beach and forming a thin cover on the cliffs and the hinterland. Along the S coast of the El Grove peninsula, on the tombolo, and on mainland areas in direct contact with the Atlantic Ocean, dunes have formed. In the south-eastern part of the Peninsula del Grove, wind-blown sands have been found at heights up to about 100 m.

Tidal flats

The largest tidal-flat area is found in the Ensenada del Grove (Fig. 2), the deep embayment enclosed by the mainland, the El Grove peninsula, and the tombolo connecting the peninsula with the mainland; this area contains one larger island (La Toja) and many smaller ones.

The tidal flats, which are separated by tidal channels, occupy strips 50—350 m wide along the coasts and the islands. The large channels in the lower tidal flats have widths up to about 50 m and depths of 3 to 4 m, the smaller ones in the higher parts are 2—10 m wide and often not more than half a metre deep.

The Ensenada sediments show a large variety of grain sizes. Sand is found in the lower parts and channels of the tidal flat and on beaches; silt, dark in colour beneath the surface and smelling of H_2S, occurs in the higher parts. In these higher parts of the tidal flats, *Arenicola* — with its characteristic small heaps of excrements at the surface — is common. Gravel is found near remnants of terraces, near outlets of small rivers, and in some deep channels.

The tidal-flat sequence shows the usual fining-upwards picture, in which an alternation of silty and clayey laminae with sandy layers may occur. Wave ripples occur in the sandy layers. Large numbers of pelecypods and gastropods in layers 5 to 15 cm thick lying about 10 to 20 cm deep are common. The occurrence of shells at the surface has strongly decreased because of the local habit of collecting shellfish, which has also led to the obliteration of the original sedimentary structures.

The subsoil of the Ensenada del Grove consists of non-marine kaolinitic clay[1]. In the eastern part and on the adjoining mainland, where it is worked in clay pits, the intercalation of sandy and gravelly layers indicates a sedimentary origin. This clay probably forms part of a bedded slope deposit washed down from the neighbouring hills during the Pleistocene (Nonn, 1964, 1966; Pannekoek, 1966). In the western part of the Ensenada the occurrence of fresh and only partially weathered feldspar and biotite points to weathering *in situ* of the underlying granite or to very minor transport. Sedimentary structures were not observed here. The tidal-flat area is disturbed

[1] In the adjoining salt marshes illite and gibbsite are the main clay minerals, apart from some kaolinite (report by Dr. P. Hartman, Department of Geology, Leiden University).

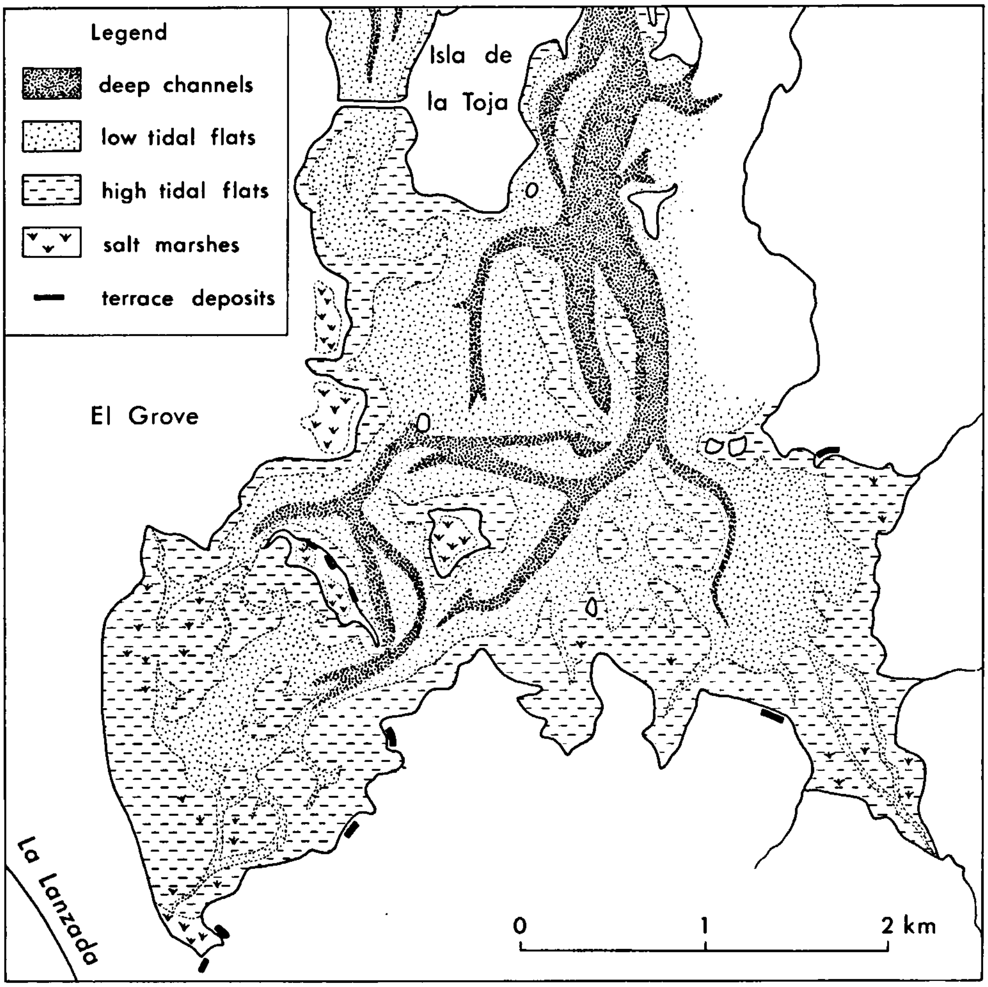


Fig. 2. Sketch map of the tidal flats of the Ensenada del Grove, modified after D. J. Wiersma (1967). The boundary lines are approximate. Scale about 1:40,000.

not only by digging for shellfish but also by digging for the kaolinite underlying the tidal deposits, and by pollution with debris from neighbouring brick works.

In various places on the mainland and some islands the tidal flats are bounded by low cliffs in terrace deposits. These cliffs have supplied pebbles to the adjoining beaches. The origin of these pebble deposits will be discussed in the chapter on pebble roundness. Low cliffs are also found where the sea has attacked the salt marshes occurring locally on the landward side of the tidal flats. From these places mud pebbles have been supplied to the beaches and flats.

The Ensenada del Grove is only a few centuries old; the fine-grained sediments of the Ensenada could only be deposited after the tombolo had formed.

Another but much smaller tidal-flat area is found in the deep embayment of Villanueva. Strong tidal currents occur in the narrow channel connecting this area with the open water of the ria, leading to the formation of asymmetric megaripples.

GRANULOMETRIC COMPOSITION

Remarks on methodology

The grain-size composition of about 100 samples was determined. Because different students worked on this project in different years, the analyses were not performed according to a uniform system over the whole area. The grain-size analyses of the samples from the shores of the ria north of the El Grove Peninsula and from the northern part of the Ensenada del Grove were done on the whole sediment, i.e. including the gravel-size fractions, whereas the laboratory analyses of the sediments along and south of the peninsula and of the inner part of the Ensenada concerned only the material finer than 2 mm, the percentage of the granule-pebble fraction of most samples having been estimated in the field. This has no effect for fine-grained sediments, such as occur locally in the Ensenada, since they lack gravel-sized material

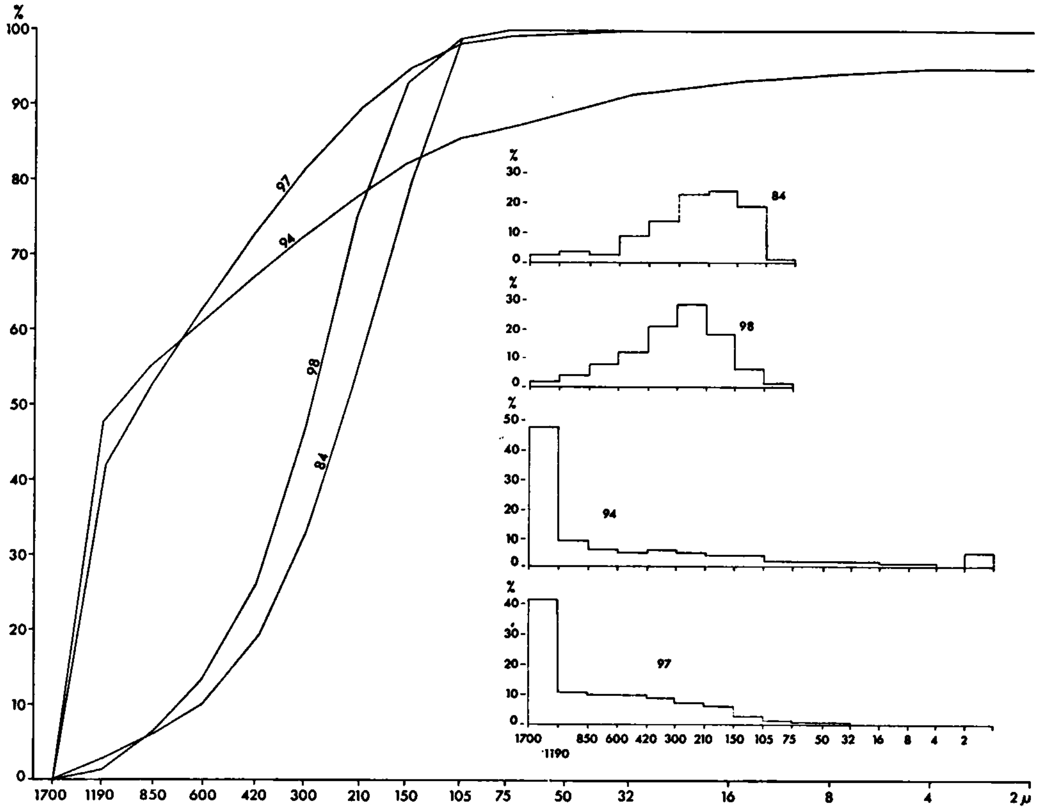


Fig. 3. Grain-size composition of four samples of the tidal flats of the Ensenada del Grove. Samples 84, 98: fine-grained; samples 94, 97: coarse-grained (granules not shown).

(Fig. 3, samples 98 and 84), but when there is a substantial proportion of granule and pebble-sized grains the cumulative curve shows a cut-off tail (Fig. 3, samples 94 and 97). This also holds for the sediments from El Grove Peninsula, the grain-size analyses of which were also limited to the sand-silt-clay-sized fractions, resulting in cumulative frequency curves with tails at the fine and coarse ends (Figs. 4, samples 142, 143) and curves with a cut-off tail at the coarse side (Fig. 4, samples 104, 107, 129, 136 and 139). For such cases, the laboratory boundary of 1700 micron is not a natural one. Consequently, the parameters derived from the grain-size analyses from the El Grove Peninsula and the Ensenada are not directly comparable with those from the other ria sediments.

Grain-size characteristics of the beaches

The ria beach sands are in general coarse-grained, M-values of 1000—2000 micron being fairly common, although values of 2000—3000 micron and even larger occur as well.

In various cases, as could be expected, beaches open to the prevailing winds and thus to stronger wave action, consist of coarser sand than protected beaches. Sands from small arcuate beaches between protruding tors capes are sometimes even fine-grained and well sorted (Fig. 5, sample 11). From beaches in other parts of the world it is known that a longshore movement of water by winds may result in a longshore transport of sediment. Sand grains may even bypass rocky points and "continue along the shore provided that the water off the points is not very deep near shore" (Shepard, 1963, p. 182; Ingle, 1966, p. 123). The great differences in grain size of neighbouring beaches show that in the Ría de Arosa such longshore currents are absent or only of minor importance. On protected beaches the beach material is only affected by transversal waves and there will be hardly any lateral transport and mixing of material from neighbouring beaches. This conclusion also follows from the heavy-mineral composition, and is in agreement with the findings of Arps & Kluyver (1969) on the opposite shore of the ria.

Where beaches are most exposed to surf action, as on the southern shores of Isla de Arosa, the grain-size composition has its modal class in the 850—1100 micron size grade. On protected beaches, along the high-water mark, the 300—420 micron and/or 420—600 micron size grades are predominant; where beaches are moderately open to prevailing winds, the 600—800 micron size grades reach the highest per-

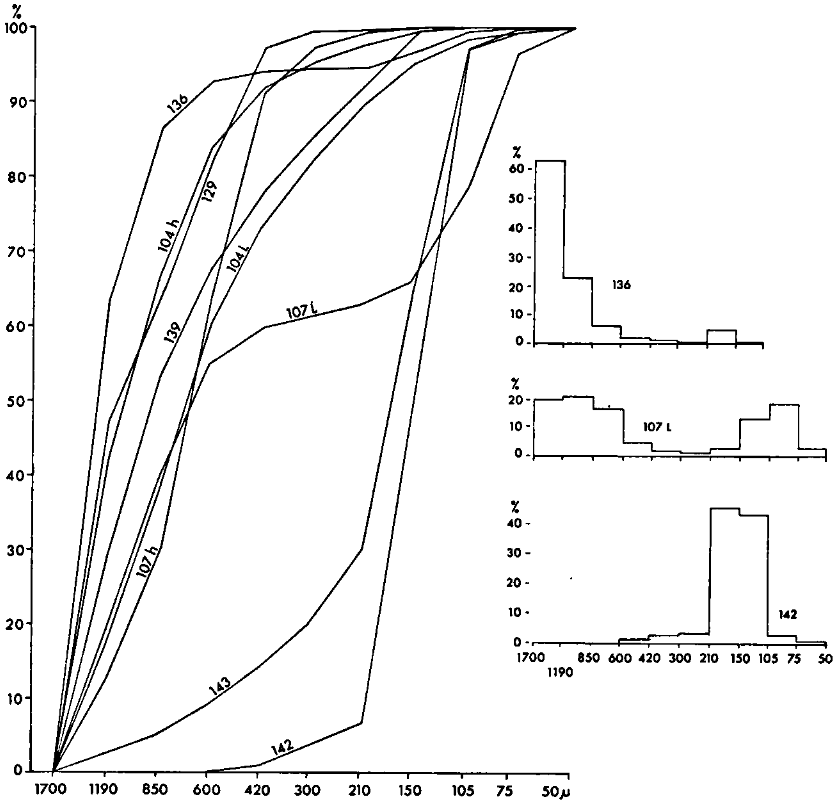


Fig. 4. Grain-size composition of beaches of the Peninsula del Grove (samples 142, 143: fine-grained; samples 129, 136, 139: coarse-grained, granules not shown) and from the island of La Toja (samples 104, 107).

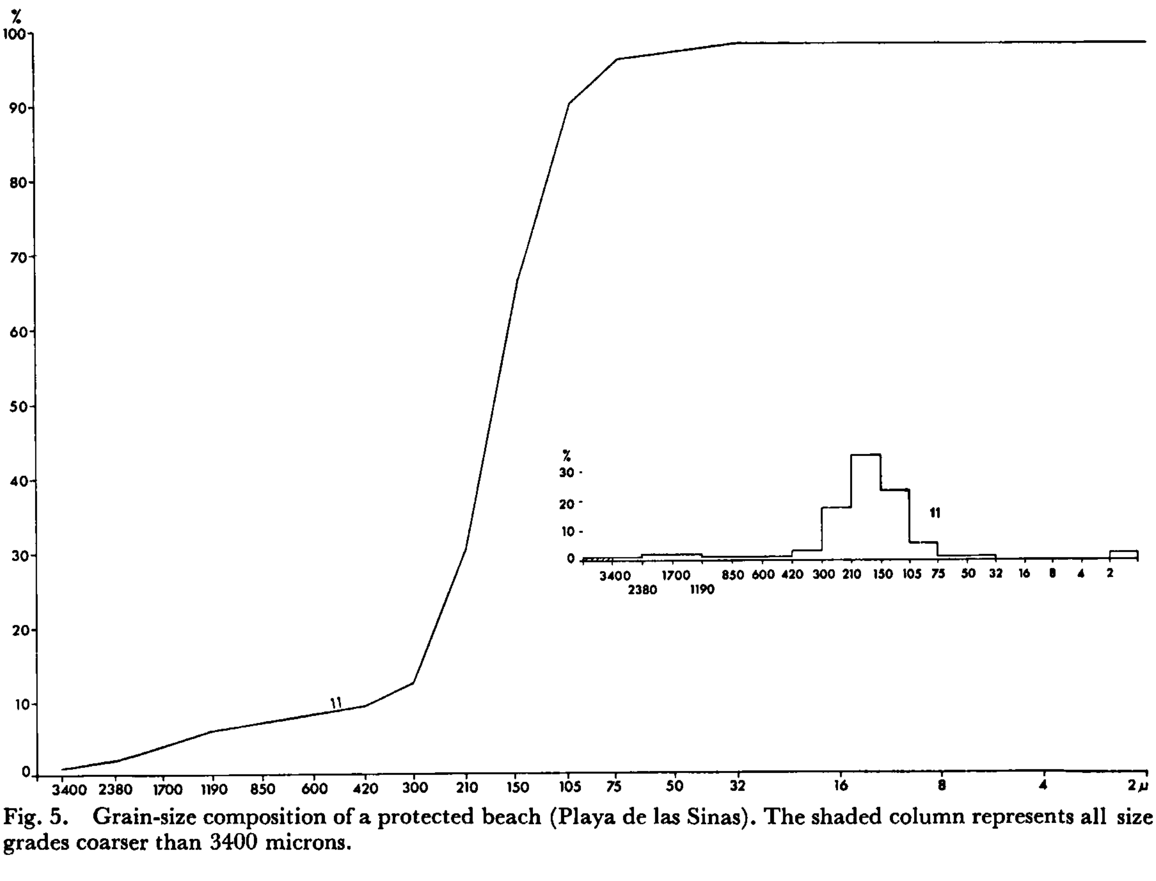


Fig. 5. Grain-size composition of a protected beach (Playa de las Sinas). The shaded column represents all size grades coarser than 3400 microns.

centages. However, the grain-size composition of samples from the Lanzada beach, which is exposed to the ocean swell, do not follow this rule (samples 142 and 143 in Fig. 4): the average Md of five samples along the high-water mark (HWM) is 373, with an average sorting value of 1.46, and for five samples taken along the low-water mark (LWM) these values are 284 and 1.70 respectively.
Table I shows some parameters of beach sediments of the Playa de las Sinas, which was exposed to strong northern winds at the time of sampling, and from the beaches S of the mouth of the Umia River, protected by islands, where wave-action and depth are limited and the content of the fine size grades is larger.

TABLE I

Open beach
(Playa de las Sinas)

locality (Plate IV)		Q_1	Md	Q_3	So
12	LWM	4450	2020	530	2.90
15	HWM	4000	1600	860	2.15
17	LWM	2400	640	215	3.34
23	HWM	4100	1650	590	2.63
28	LWM	3750	1380	350	3.26
31	HWM	3300	1850	1120	1.71

Protected beach
(S of Umia)

locality (Plate I)		Q_1	Md	Q_3	So
63	LWM	1210	575	335	1.90
	HWM	2710	1380	685	1.97
	(tombolo)				
66	LWM	1220	180	105	3.50
	HWM	2440	1360	740	1.82
69	LWM	520	185	143	1.90
	HWM	2125	1385	885	1.55

Grain sizes at the high-water and low-water marks

For all the beaches samples were taken from the top layer near both the HWM and the LWM. Comparison of the average results of the grain-size analyses of the HWM- and LWM-samples from the inner-ria beaches, as demonstrated by the frequency curves (Fig. 6), shows that there is hardly any difference between the amounts of grains > 1000 micron, that grains < 75 micron are virtually absent, but that grains of 300—1000 micron occur on the average 7% more frequently at the HWM than at the LWM, whereas the percentages of 75—300 micron grains are on the average 9% higher

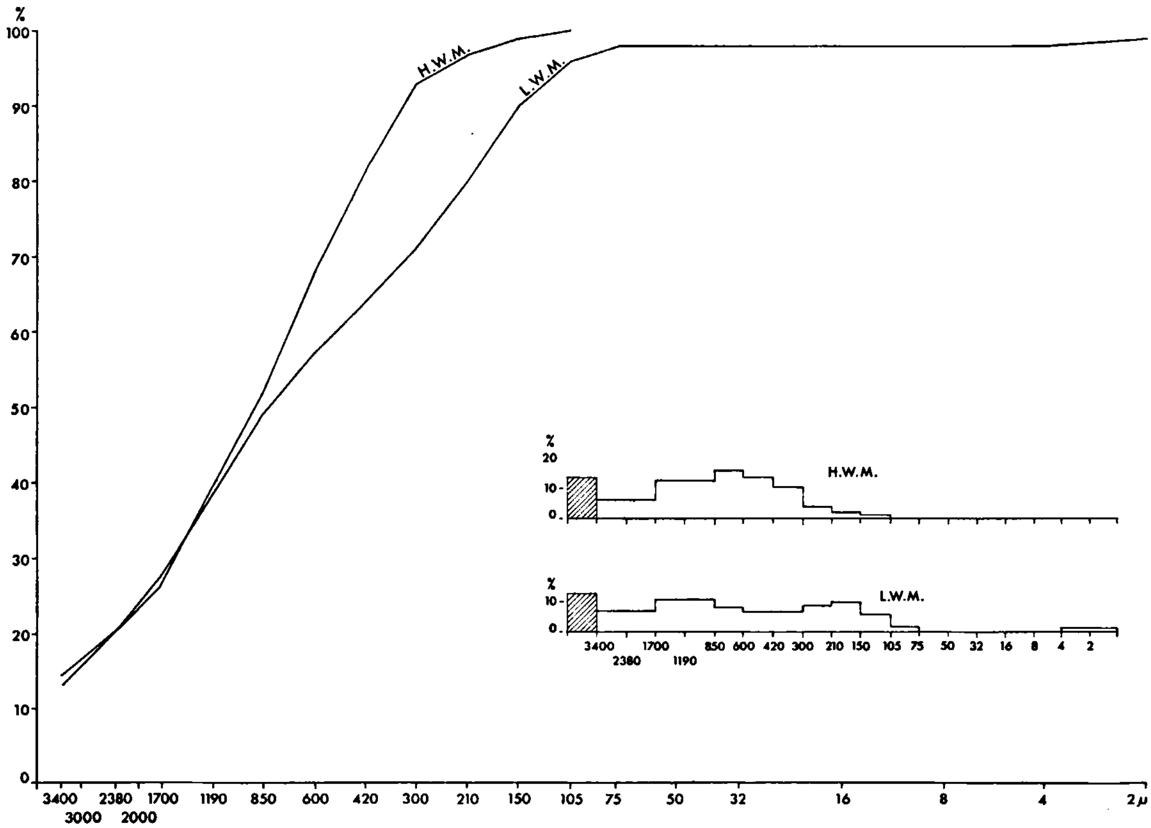


Fig. 6. Average grain-size composition of high-water mark and low-water mark sediments on beaches of the inner ria. The shaded column represents all size grades coarser than 3400 microns.

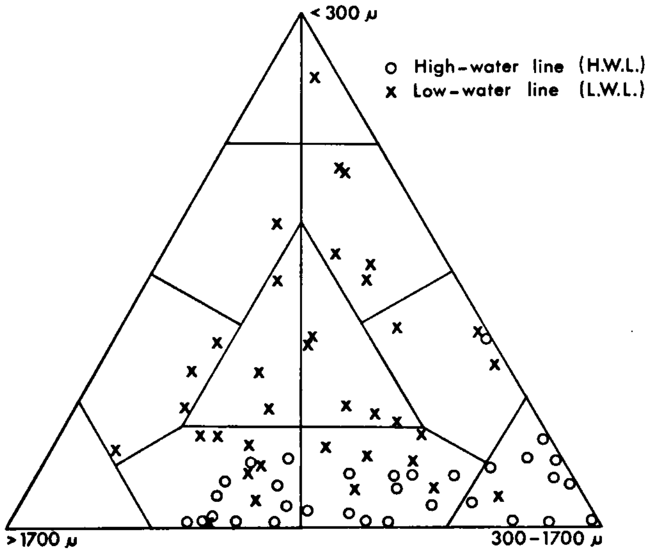


Fig. 7. Triangle diagram of grain sizes of high-water mark and low-water mark sediments of the inner ria.

at the LWM than at the HWM. A triangular diagram (Fig. 7) also shows the difference between the HWM-samples, which are located mostly toward the 300—1700 micron corner, and the LWM-samples, which are found practically all over the triangle. This difference may be explained by the fact that all sand grains, including those > 300 micron, are transported landward by the surf, whereas grains < 300 micron are washed back towards the LWM. These latter grains are not washed farther down into deep water, which implies that also the relatively fine-grained sand grains are not transported in suspension but as bed load.

The differences in grain size and in sorting between

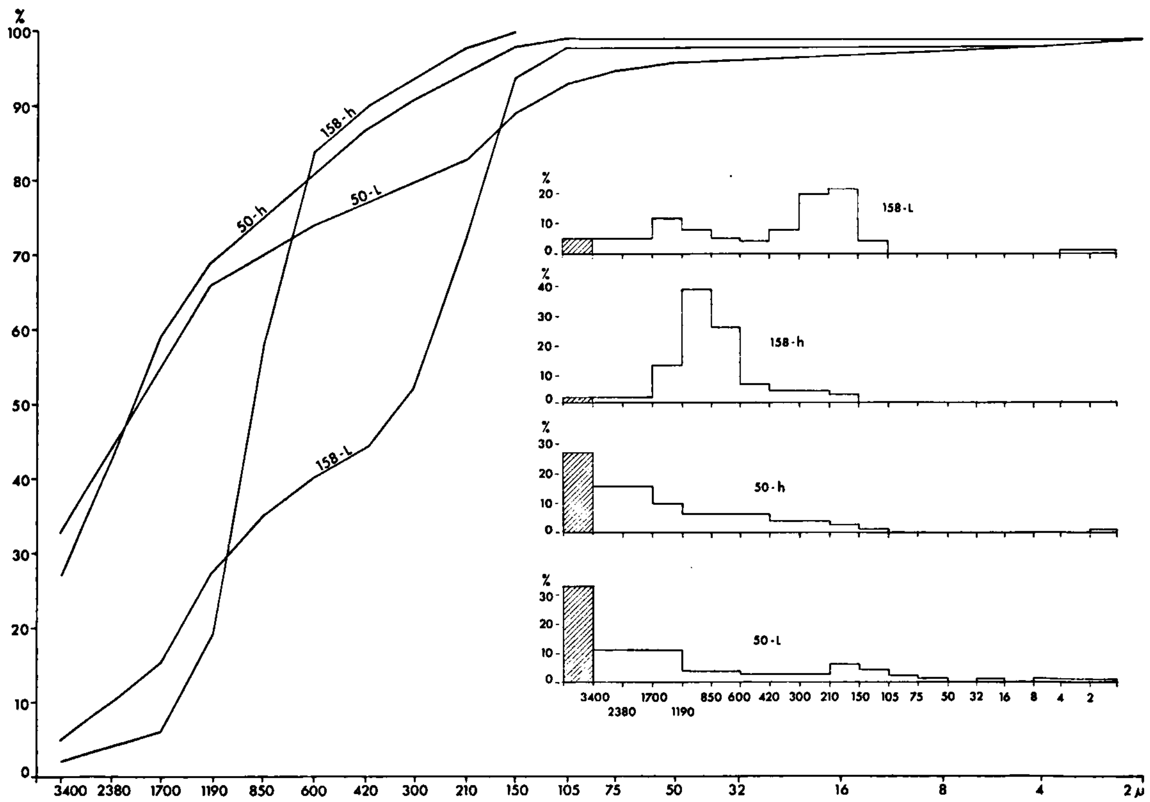


Fig. 8. Grain-size composition of high-water mark and low-water mark sediments of open beach (samples 158 h, l) and protected beach (samples 50 h, l). The shaded column represents all size grades coarser than 3400 microns.

HWM- and LWM-sands is shown by samples from various open beaches (Fig. 8, samples 158 l and 158 h) and from a protected beach, where the differentiation in the sands is less marked: Fig. 8, samples 50 l and 50 h. Especially on the protected beaches S of the Umia River, Q_3-values of LWM-samples show much lower values than those of HWM samples (Table I). Great differences between HWM-and LWM-samples occur in the beach samples from La Toja (Fig. 9). The HWM-samples, as far as the material finer than 2000 micron is concerned, all show a reasonable degree of sorting, whereas the LWM-samples vary from reasonably sorted to definitely badly sorted grain-size compositions.

of the beach samples show a bimodal grain-size distribution with respect to sand and granule-size grades; the sand fraction itself, however, is mostly rather well sorted, as is shown by sample 11, a beach sand at the LWM taken from the central part of an arcuate beach between tors capes (Fig. 5). Sorting of sand is also moderate to good (1.21—1.52 at the HWM, 1.33—1.59 at the LWM) in sands free of coarse material (>2000 micron) along the La Lanzada beaches, i.e. at the ocean coast.
Where granite tors barely rise above the LWM, granules of disintegrated granite are supplied near the LWM. If wave action is weak, the beach samples taken at the LWM are much coarser than those of the

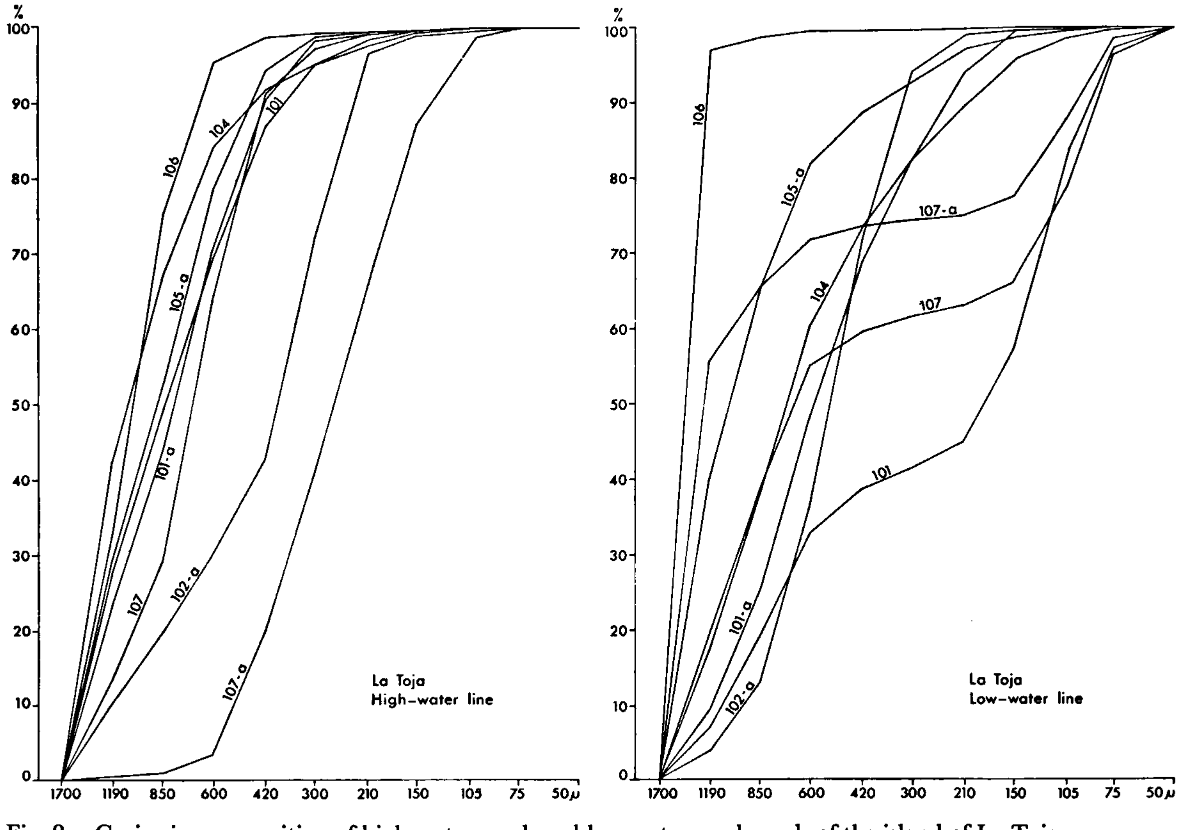


Fig. 9. Grain-size composition of high-water mark and low-water mark sands of the island of La Toja.

Grain-size composition of the beaches as related to that of the cliffs

Where beaches are bounded by cliffs, the grain-size composition is strongly dependent on that of the cliffs. If these cliffs consist mainly of terrace material, their granulometric composition shows a strong resemblance to recent beaches, apart from the fact that in the terraces, material smaller than 100 micron is found in a higher proportion than on the beaches. If, however, the cliffs consist of weathered coarse-grained granite, a certain supply of granules reaches the beach. Since these granules are not moved by ordinary waves, most

HWM. Examples of this situation are found on the protected coastal section between Villanueva and Cambados:

TABLE II

Locality (Plate I)		Q_1	Md	Q_3	So
49[a]	HWM	1410	1110	885	1.26
	LWM	3700	1410	515	2.24
54	HWM	1320	860	500	1.62
	LWM	4000	1720	830	2.19
55	HWM	915	685	485	1.37
	LWM	5100	1610	510	3.16

These figures clearly show that on these beaches granules are not moved by the waves and that only the sand fraction is washed out and carried up to the HWM. Accordingly, the sands are better sorted along the HWM than along the LWM.
The opposite is found on the cuspate foreland of El Vado, which is exposed to winds and surf (Phot. 1). These samples show a bimodal mixture of granules and coarse sand. Waves wash the spit, and material is deposited on the southern slope when the wind is from the N and on the northern slope when the wind is from the S. The coarsest material is found at the HWM.

TABLE III

		Q_1	M	Q_3	So
El Vado	HWM	9500	3980	700	
	LWM(S)	3700	700	270	3.70
	LWM(N)	1850	430	215	2.92

That the grain size is also dependent on other factors is shown by the composition along LWM and HWM on the small sandy island of Jidoiro Arenoso. The accumulation beaches show a bimodal sediment at the LWM, whereas at the HWM the granule fraction is missing and a well sorted coarse sand is found. In all probability, the beach sands are in this case derived from eolian sands in cliffs on this small island.

TABLE IV

		Q_1	M	Q_3	So
Jidoiro Arenoso	LWM	3050	1900	325	3.06
	HWM	520	425	345	1.23
	HWM	500	372	282	1.32

Grain-size characteristics of the tidal flats (Ensenada del Grove)

The sediments of the Ensenada del Grove, i.e. the tidal-flat area (Fig. 2), show a wide variety of grain sizes; the kind of sediment is dependent on the type of sub-environment in the embayment. Fine-grained sand is found in the higher and coarse-grained sand in the lower parts, especially in the channels. Gravel is mainly found near scarps of terraces, as winnowed relict sediments, and in some deep channels, e.g. between the island of La Toja and El Grove Peninsula.
The best-sorted sands are those from a sandy beach with So=1.4 and Md=1100 micron, and from channel deposits with So=1.4 and 1.6 and Md-values of 290 and 700 micron, respectively. Silt from the salt marsh, with 25 per cent <2 micron, So=3.3, and Md=32 micron belongs to the worst sorted material in this area.
Sands from a shoal in the Ensenada del Grove tidal flats show a granulometric composition devoid of grains >210 micron.
Three samples from a boring in the Ensenada del Grove reaching a depth of 70 cm, have So-values of 2.3, 4.3, and 3.8, with Md-values of 1190, 150, 27 micron from bottom to top, thus showing the fining-upwards characteristic of tidal-flat deposits.
Since the intertidal zone is flanked by a coastline behind which granitic bedrock with a moderate relief is exposed, the tidal-flat sediments of the Ensenada del Grove and of other embayments in the area belong to DeVries Klein's (1963) Fundy type. They differ texturally from those of the Dutch Wadden Sea, being coarse grained in the Ensenada in contrast to the fine-grained sediments of the Wadden Sea. This divergence is accounted for by the differences in coastal geology and geomorphology (DeVries Klein & Sanders, 1964).

Eolian sands

Only one example will be given of eolian sand derived from a coarse-grained beach on the Isla de Arosa. The analysis shows that the wind picks out grains of a very specific and narrow grain-size range, so that the dune sand is much finer grained and much better sorted than the adjoining beach.

TABLE V

Locality		Q_1	M	Q_3	So
150	HWM	2500	1660	390	2.53
	LWM	1785	885	320	2.35
152	dune	460	352	255	1.35

The frequency graph shows the difference between these samples very clearly (Fig. 10).

MORPHOMETRY

Roundness of sand grains

For 18 samples from different localities, roundness values were determined of 4 size grades of quartz grains: 50—300, 300—850, 850—1700, and 1700—4080 microns.
In the fine-sand size grade (50—300 micron), apart from one sample from a cliff with angular grains, all samples showed subangular grains, the majority toward the angular side. The coarse-sand size grade (300—860 micron) is subangular; the very coarse-sand size grade (850—1700 micron) is subangular at

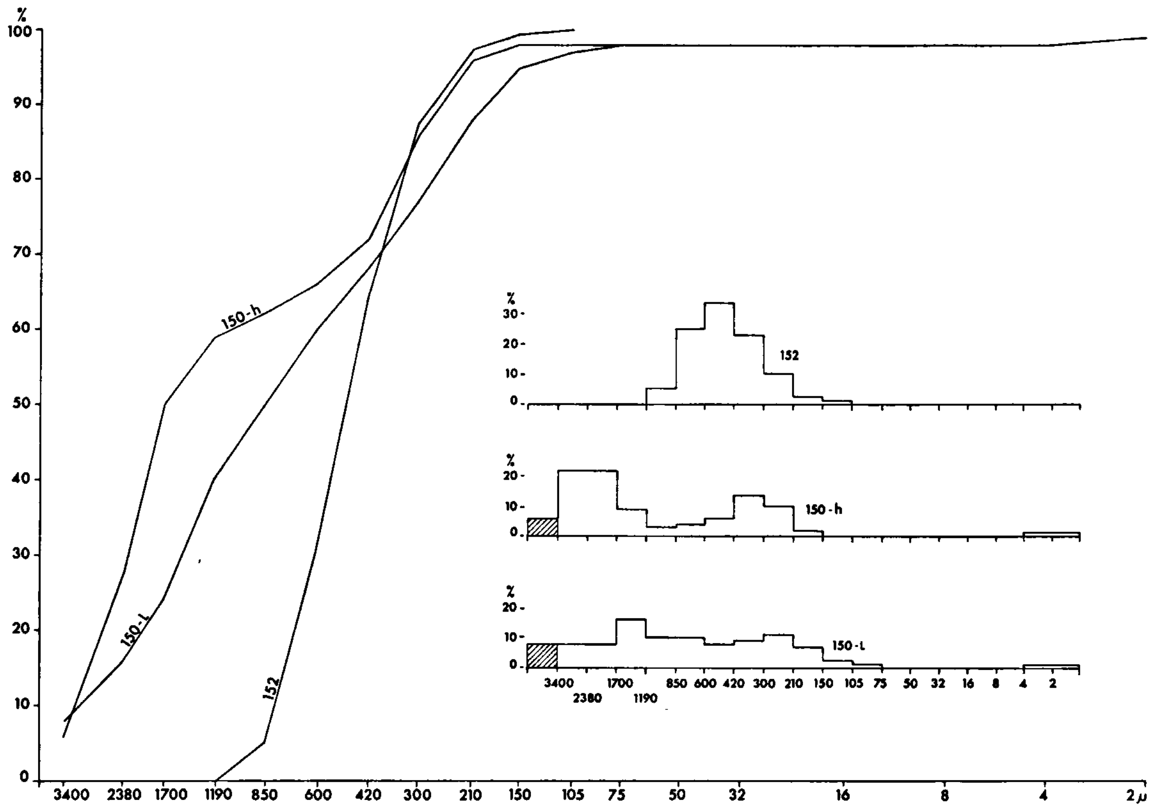


Fig. 10. Grain-size composition of beach samples (150 h, l) and dune sand (152) from the Isla de Arosa. The shaded column represents all size grades coarser than 3400 microns.

15 and subrounded, toward the subangular side, at 3 stations; granules of 1700—4080 micron show similar roundness values. These degrees of roundness indicate the absence of any appreciable amount of abrasion. Along the Lanzada beaches, however, the rho-values, determined for grains of 500—1000 micron, must be classified as subrounded and rounded. The dune sands along this coast, as well as the eolian sands on El Grove Peninsula, even consist of rounded and well-rounded grains.

These observations permit a clear differentiation between:

(a) subangular beach sands, as derived from weathering of intrusive and metamorphic rocks;

(b) subrounded and rounded beach-sand grains from the high-energy beach of La Lanzada;

(c) rounded wind-blown sands which are derived from this beach.

The roundness value of probably wind-blown sands in the ria area itself, as one sample on Isla de Arosa shows, hardly differs from that of the beach sands.

Roundness of pebbles

For 45 localities, the roundness of 50 quartz pebbles varying in length from 16 to 120 mm, was measured; from these readings, Cailleux's roundness index $2r/L \times 1000$ was calculated.

Quartz pebbles are found on the beaches only where the latter are bounded on their landward side by abrasion cliffs containing pebbles (Phot. 2). These pebble deposits in the cliffs represent either older marine terraces or colluvium and older slope deposits partially deriving from older marine terraces.

The highest (fluvio-) marine terrace in the area lies at a height of about 30 m near the mouth of the Umia River (Nonn, 1958; Bisdom, 1967), but is not in direct contact with the beach. Many marine terraces are situated at 12—15 m and grade downward into an extensive level only a few metres above the present sea level (Nonn, 1958). This level is considered to represent the Epi-Monastirian level (last interglacial) and is exposed in many of the low cliffs. The subangular quartz pebbles of the bedded (torrential) slope deposits near Noalla, too, were partially reworked by the waves at the same time and now form low marine terraces around the Ensenada del Grove (Fig. 2).

The quartz pebbles of the terraces at 12—15 m and lower down are probably derived from colluvium. Bisdom (1967) mentions that many of the slopes in the hinterland are covered by colluvium containing angular quartz pebbles supplied by quartz veins in the granite. It must have been some of these quartz fragments that underwent marine reworking, most recently during the last interglacial.

Consequently, we would expect the pebble deposits exposed in the cliffs to consist of mixtures of angular to well-rounded pebbles, and this is what we actually find in various cliff sections (Table VI, Fig. 12). The medium roundness values vary from 206 to 384[1].

TABLE VI

Locality	Roundness
Beach Playa de las Sinas	302
Beach Playa de las Sinas	354
Average for beaches	339
Cliff Playa de las Sinas	294
Cliff at location 62	345
Average for cliff sections	292

Beaches exposed to considerable wave action can be expected to show higher roundness values, since the more angular fragments from the cliffs undergo further rounding on the beach. Indeed, various beach samples (but not all) show lower percentages of the least-rounded pebbles. The medium roundness values for pebbles from such beaches lie between 284 and 390. Fig. 11 shows that roundness of beach pebbles is lower in the more protected parts of the ria: the inner ria, the area protected by the Isla de Arosa, and the Ensenada del Grove. Only where terraces containing many rounded pebbles are abraded do the beaches also show higher roundness values. Along the present coast of the Ensenada del Grove, where roundness indices are generally low (92, 121, 205), one sample from a marine terrace exposed on a small island shows a considerably higher index (291). This implies that marine influence was stronger when the terrace sediments were reworked by waves than it is now. Formerly, when there was not yet a tombolo connection between the mainland and El Grove, the ocean had a free entrance into the present Ensenada area. Since there are only a few of these relatively older cliffs and erosion is weak in this area, the influence of these deposits of better-rounded pebbles on the present beach-pebble assemblages is small.

MINERALOGY: HEAVY MINERALS

Introduction

To investigate the origin of the beach sands, the 50—500 micron size grade of about 150 samples from mainland and island beaches were analysed to determine their heavy-mineral composition. As for the granulometric investigations, samples from the LWM and the HWM as well as from cliffs bordering the beach, were analysed; the heavy-mineral composition was determined by line-counting of 100 translucent grains.

It is clear from Plate I that there is great variation in the heavy-mineral compositions of the samples and that areas with different heavy-mineral associations can be distinguished along the ria beaches. Moreover, there is often a marked difference in composition between LWM- and HWM-samples.

The observed differences in heavy-mineral composition could result from differences in provenance but could also be due to differences in grain-size of the samples. It should be kept in mind that counts of 100 grains in the 50—500 micron size range include grains of different sizes but each grain counts as one, irrespective of its size; for instance, a small grain of zircon and a large grain of tourmaline are both counted as one grain. To find out whether the differences in heavy-mineral composition are primary, i.e. dependent on the provenance, or result from the grain size of the sample, the heavy-mineral composition of several size grades of 34 samples was determined.

Fractionated heavy-mineral analysis

As for the grain-size analyses, the fractions chosen for the fractionated heavy-mineral analyses are not uniform for the whole area, since various students worked on this subject in different years. The samples from the ria proper and from the islands were divided into 5 size grades: 50—75, 75—150, 150—300, 300—420, and 420—500 microns, whereas the material from the El Grove area was divided into 4 size grades: 50—105, 105—210, 210—420, and 420—500 microns. Plate II shows only some examples from the former area. Some samples did not contain sufficient material of one or more size grades to permit heavy-mineral analysis.

Comparison of the composition of different size grades of one sample shows that various minerals are more or less bound to one or two size grades, whereas other minerals are more evenly distributed over various size grades. It is well-known that zircon is generally concentrated in the fine-grained size grades. Indeed, sample 68 LWM clearly shows that zircon, dominant in the 50—75 micron size grade, is virtually absent among grains coarser than 300 micron. The reverse may be said of tourmaline, which seems to be concentrated in 300—500 micron size grades and only occurs in small amounts in the finer size grades (with the exception of two samples extremely rich in tourmaline). Hornblende, in locality 68, is found in only small amounts in the 50—75 micron, and in much larger quantities in the coarse size grades. Andalusite and sillimanite, and to a lesser degree staurolite, preferentially occur in sizes larger than 150 micron. Epidote, on the other hand, seems to be more frequent in the medium-size grades (75—300 micron). Plate II therefore shows the susceptibility of various minerals to variations in grain size.

Heavy-mineral associations

When the vertical columns of Plate II are considered separately, in other words when the composition of the

[1] The highest roundness value, 428, was found on pebbles in a black humic layer, at the eastern end of Playa de las Sinas.

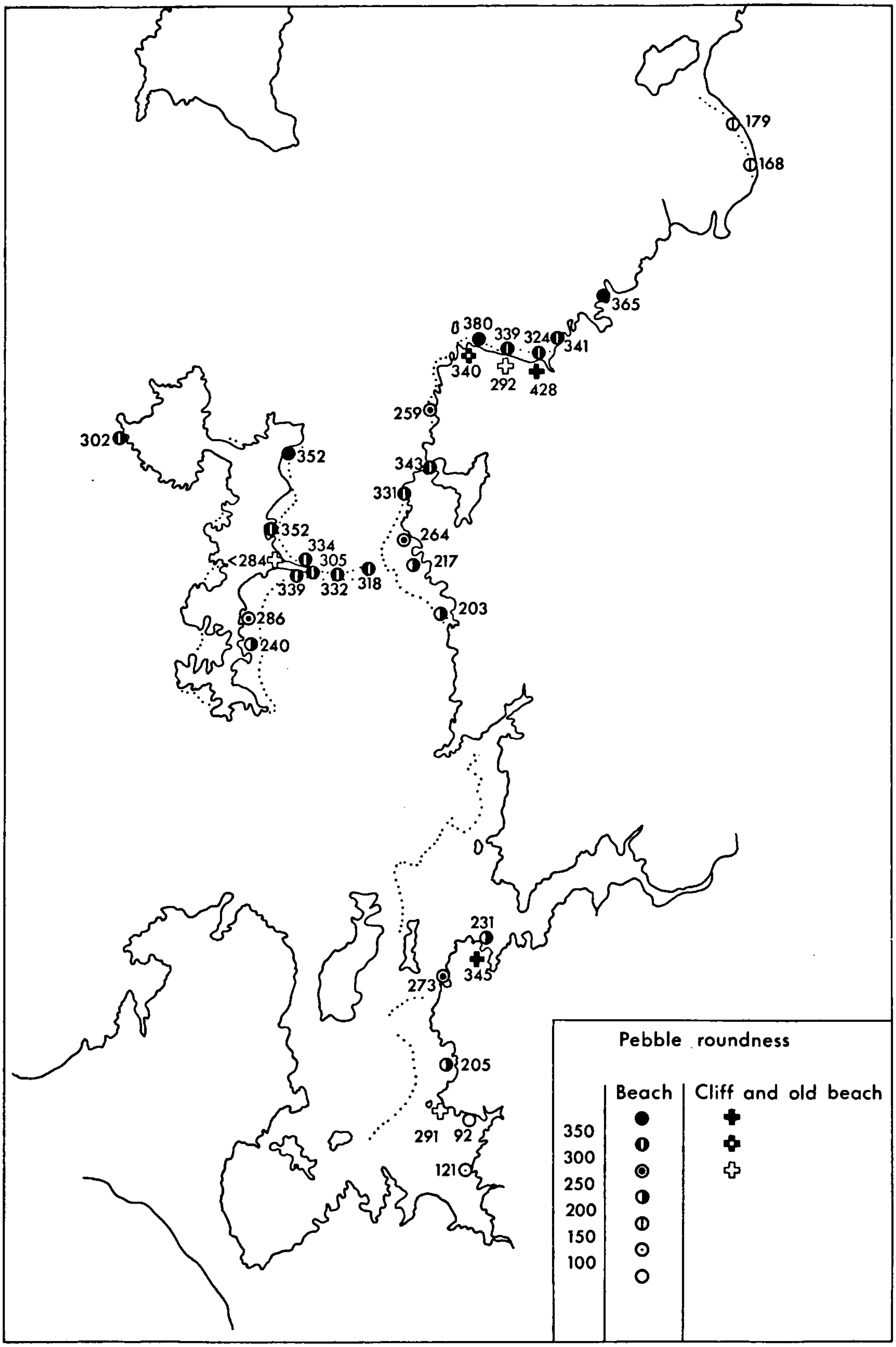


Fig. 11. Average roundness values of beach and cliff pebbles of the south-eastern shore of the Ría de Arosa. Approximate scale 1:100,000.

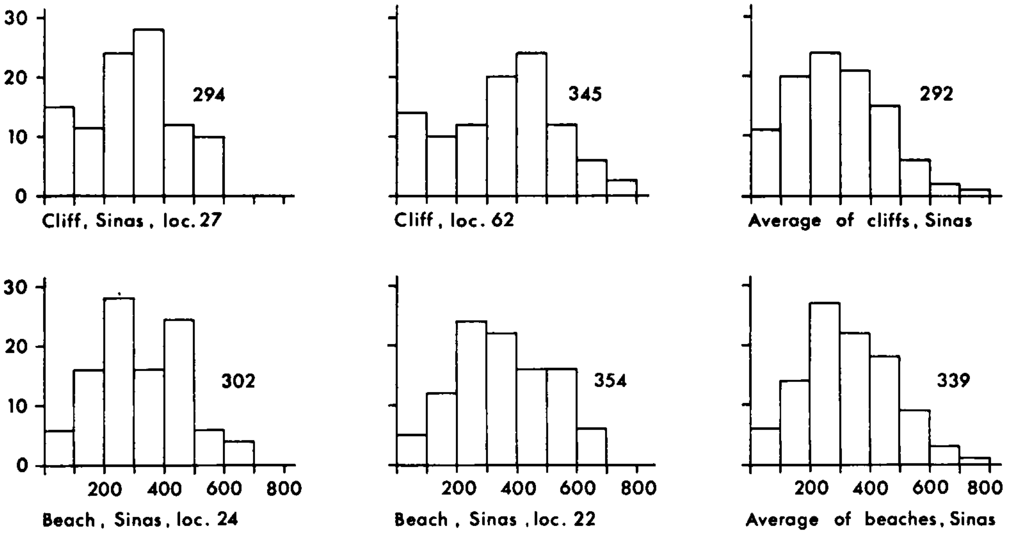


Fig. 12. Frequency distribution of pebble-roundness values. Upper row: cliffs, lower row: beaches.

same size grades of different samples is compared, it is clear that there are great differences that must be primary and thus related to provenance. Sample 1 from LWM and HWM clearly shows a dominance of tourmaline; samples from locations 68-tombolo, 68-l, and 68-h have a high proportion of hornblende. In sample 54 epidote (+alterite), although not dominant, occurs in larger quantities than in the other samples. In most of the remaining samples the metamorphic mineral group (staurolite, kyanite, andalusite, sillimanite) is distinctly dominant, although the proportions of these minerals within the metamorphic group vary.

Since the major differences in heavy-mineral composition are related to certain regions in the ria area, as is clearly shown by Plate I, the various heavy-mineral assemblages may be grouped into regional associations (Koldijk, 1968, p. 111). On the grounds indicated above, we distinguish four main associations:

1. metamorphic association (M)
2. hornblende association (H)
3. tourmaline association (T)
4. epidote association (E).

Metamorphic association

If zircon is excluded, more than 50 per cent of the heavy minerals belong to the group of metamorphic minerals: staurolite, kyanite, andalusite, and sillimanite. Of these minerals, staurolite is generally dominant in the ria area proper, whereas in the beaches at the southern and western sides of the El Grove Peninsula, andalusite is dominant.

The beach sands from the rocky coast S of Playa de la Lanzada (localities 146, 147, and 148) show a dominance of andalusite (67—86%), with garnet in second place (3—27%) but only at LWM, and staurolite third (1—18%). This assemblage was only found in this coastal area, and additional heavy-mineral investigations will be required to determine whether it represents a separate sub-association.

Relatively high percentages of garnet were found in the western part of the El Grove Peninsula (localities 127, at the HWM, 131 at both the LWM and the HWM, and 133, only at the HWM).

The M-association is subdivided into a number of regional sub-associations based on the relative amounts of the various metamorphic minerals and on the admixture of some other heavy minerals. The compositions of the sub-associations are, however, largely overlapping. Sometimes even a sample occurring within the region of a certain sub-association shows a heavy-mineral composition belonging to a different sub-association. Such cases should be attributed to particular local conditions. The areas occupied by the sub-associations therefore only show a general trend in their compositions rather than sharply defined percentages of certain minerals. The following sub-associations within the M-association could be distinguished:

a. Isla de Arosa sub-association
b. El Vado sub-association
c. Playa de las Sinas sub-association
d. Jidoiro sub-association
e. El Grove sub-association.

a. Isla de Arosa sub-association. — This sub-association, together with the El Vado sub-association, represents the M-association in its purest form. In this sub-association, staurolite strongly dominates over the other metamorphic minerals.

Composition range:

	percentages	average
metamorphic minerals	65—81	73
staurolite	39—73	53
kyanite	2—14	6
andalusite	5—22	13
sillimanite	0— 3	1

The association is found along the E coast of the Isla de Arosa, N of the El Vado cuspate foreland.
Fractionated analyses show (Plate II, locality 181, at the LWM and in cliff) that among the metamorphic minerals staurolite is slightly concentrated in the coarser size grades, that kyanite does not occur in grains larger than 300 micron, that andalusite is found mainly in the 150—420 interval, and sillimanite, although ubiquitous, is most strongly represented in the coarsest size grade. Epidote is found in the finer, and alterite in the medium-grained size grades.

b. El Vado sub-association. — The El Vado sub-association also shows high percentages of metamorphic minerals, but staurolite is less dominant and therefore the other minerals of this group are better represented.

Composition range:

	percentages	average
metamorphic minerals	56—88	78
staurolite	4—64	28
kyanite	0—28	7
andalusite	7—44	30
sillimanite	1—39	13

This assemblage is found in the El Vado cuspate foreland (Plate III). There is a difference between the dry part of the foreland, which is no longer inundated even at storm tide, and the present beach: the staurolite content in the most recent, wet part is higher than in the older dry part of the beach: 31—64 (average 48) as against 4—34 (19) per cent, whereas the andalusite percentages are 7—31 (19) and 22—44 (35) respectively, and the sillimanite (fibrolite variety) percentages 0—11 (5) as against 3—38 (15). Roughly speaking, staurolite takes over the leading position of andalusite and sillimanite.
The sub-association of the El Vado spit is comparable to Koldijk's El Vado sub-association for the sands occurring in the channel between the Isla de Arosa and the mainland. He also mentions the relatively high amount of kyanite.

c. Playa de las Sinas sub-association. — As far as the metamorphic minerals are concerned, this sub-association is not unlike the preceding one but it is often mixed with epidote and sometimes with zircon, the latter in one case reaching 59%.

Composition range:

	percentages	average
metamorphic minerals	25—85	60
staurolite	17—54	32
kyanite	0—21	7
andalusite	1—29	11
sillimanite	1—29	10

The adjoining land samples (from colluviated terrace deposits) show similar heavy mineral compositions (Plate IV), although some are aberrant (very high epidote or zircon contents).
The occurrence of zircon together with a high content of metamorphic minerals makes this sub-association susceptible to granular variations. This explains the marked difference between samples collected at the HWM and the LWM. Four fractionated heavy-mineral analyses again show that staurolite is mainly found in the relatively coarse-grained size grades, that kyanite is only found below 420 micron, that andalusite is slightly and sillimanite strongly concentrated in the coarser size grades.
The Playa de las Sinas sub-association should not be confounded with Koldijk's Sinas sub-association of the sands on the ria bottom, which belongs to an epidote-hornblende association.
S of Playa de las Sinas, toward Villanueva (locations 47 to 51), the sub-association becomes more mixed with epidote (forming a transition to the epidote association further S) or hornblende. Great differences in heavy-mineral composition at different localities on one and the same beach show that lateral mixing of material is rare.
N of Playa de las Sinas too, the content of metamorphic minerals decreases and hornblende and/or epidote increase.

d. Jidoiro sub-association. — In this sub-association the metamorphic minerals, among which staurolite predominates, are mixed with a greater variety of other minerals i.e. garnet, epidote, tourmaline, and hornblende.

Composition range:

	percentages	average
metamorphic minerals	26—65	44
staurolite	19—50	29
kyanite	0— 6	1
andalusite	3—21	11
sillimanite	0— 5	2
epidote	7—25	15
garnet	3—24	12
tourmaline	3—15	10
hornblende	0—21	8

This sub-association is found on the islands of Jidoiro Pedregoso and Jidoiro Arenoso, and along the southern part of Isla de Arosa. As will be shown, the sub-association may be considered a mixture of the M-association with the hornblende and epidote associations. It is identical to Koldijk's Jidoiro sub-association in the bottom-sediments.

e. El Grove sub-association. — Among the metamorphic minerals, the andalusite content is often only slightly lower than that of staurolite, and in the S this mineral is often dominant over staurolite. Tourmaline is generally an important admixture, and locally other minerals (zircon, garnet, and epidote) may reach considerable percentages. In the northern part of the peninsula titanite is found in very high percentages (up to 69%) in a limited area. Such a high content of one mineral reduces the average figures mentioned for the other minerals.

Composition range:

	percentages	average
metamorphic minerals	12—67	35
staurolite	2—39	20
kyanite	0— 5	1
andalusite	3—33	12
sillimanite	0— 4	2
zircon	1—67	21
tourmaline	2—42	17
epidote	1—29	14
garnet	1—18	7
hornblende	1—19	3

The distribution area of the El Grove sub-association comprises the whole of the El Grove Peninsula. Proceeding from the Atlantic beaches S of La Lanzada, northward along the peninsula, the heavy mineral assemblages start with more than 60% andalusite and less than 20% staurolite, whereas in the northward direction andalusite decreases and staurolite increases, so that along the northern shores andalusite and staurolite become equal and in many cases, as already mentioned, staurolite is even dominant among the metamorphic minerals.
The southwestern part of El Grove is virtually free of epidote and hornblende, which is also the case S of La Lanzada. The Lanzada beach, the S coast of El Grove Peninsula, and the northwestern part of the Peninsula show some 30 per cent combined epidote and hornblende.
The E coasts of El Grove, as well as the Ensenada del Grove, show the picture in which andalusite and staurolite reach high percentages, especially in the salt-marsh and cliff samples and in those collected on the small islets. Andalusite and staurolite alternatively dominate.
The heavy-mineral composition in the Ensenada del Grove is very variable. In addition to the majority of samples, which show the El Grove sub-association, there are samples with hornblende as dominant mineral, others in which epidote is important and a few in which tourmaline + zircon predominate. This divergence may be due to the large variation in grain size found in the Ensenada del Grove.

Hornblende association

The heavy-mineral composition of the association is characterized by a high hornblende content and in many cases a considerable amount of zircon.

Composition range:

	percentages	average
hornblende	12—59	31
zircon	6—52	32
metamorphic minerals	4—24	14
epidote	3—21	9
tourmaline	1—15	7
garnet	1—18	5

The heavy-mineral composition of sediments rich in hornblende and zircon is strongly dependent of grain size. Fractionated heavy-mineral analyses demonstrate that zircon, as expected, is by far the most important mineral in the finest fraction (50—75 micron), whereas hornblende takes a relatively large share in the coarser fractions; tourmaline is found among the coarsest grains (Plate II, nr. 68, two samples at the LWM).
Beach sands assigned to the hornblende association are concentrated along the coast of the mainland S of the Umia River. Some samples from other beaches may also belong to this association, as is the case for samples from the beaches around Villagarcía and Villajuan. Koldijk's Ulla, Rianjo, and Caldas associations in the bottom sediments are also characterized by high hornblende percentages. The relatively high hornblende percentages in some northwestern beaches of the Isla de Arosa (Plate I, samples 151 and 153) reflect the relatively high hornblende percentages on the bottom of the ria W of the Isla de Arosa (Koldijk, 1968: Plate 2, stations 528, 650, and 651).
In part of the area of the hornblende association, the Ensenada del Grove, samples showing a composition with relatively low hornblende and high epidote or staurolite percentages were also collected. These samples may derive from eroded cliffs or soils rather than from a direct supply by the Umia River.
From Koldijk's work (1968) it is known that the H-association (his Umia association) extends from the mouth of the Umia far to the W on the bottom of the ria. High hornblende contents also occur in the northern part of the ria (Rianjo association) and, together with epidote, in the Ulla estuary.

Tourmaline association

This heavy-mineral association, found only in three samples, is characterized by the occurrence of high percentages of tourmaline; these samples were taken on Cortegada Island.

Composition range:

	percentages
tourmaline	41—59
metamorphic minerals (either staurolite or andalusite dominant)	18—41
epidote	2—12
hornblende	0—18

The results of fractionated analyses are shown in Plate II, Locality 1 at the LWM and HWM.
Samples from the bottom of the ria near Cortegada (Koldijk, 1968) have a very different composition: relatively high percentages of hornblende (17—50) and epidote (10—23), and low values of tourmaline (2—7). This clearly shows that the source of the Cortegada beach samples should be sought not in the Ulla River sediments but in the rocks of the island itself.

Epidote association

This association is characterized by relatively high percentages of epidote plus alterite (the latter component to be considered as a microcrystalline aggregate of epidote), metamorphic minerals with much staurolite, and occasionally much hornblende.

Composition range:

	percentages	average
epidote	10—44	24
alterite	2—33	17
(epidote and alterite together at least 25%)		
zircon	6—50	17
staurolite	3—37	14
other metamorphic minerals	3—17	9
hornblende	1—26	8

Fractionated analysis shows some preference of staurolite for intermediate grain sizes; of andalusite, sillimanite, and alterite for coarse grain sizes, and that epidote occurs in fine as well as in coarse grain sizes (Plate II, Locality 54, LWM and HWM).
The samples of the epidote association were taken on the coastal section between Villanueva and Cambados and the northwestern part of Isla de Arosa. According to Koldijk (1968), the ria bottom around the latter area (Con de Navio) also contains sediments rich in epidote, but along the coast S of Villanueva the bottom sediments are characterized by a metamorphic association. Apparently, the beach deposits of this coastal section are locally derived from the weathered granite and the soils exposed in the low cliffs, whereas in the ria metamorphic minerals have been transported, as is also shown by the El Vado spit.

Provenance of the heavy minerals

For some important minerals in three out of the four heavy-mineral associations, i.e. the E, H, and T associations, the provenance can be established with a reasonable probability.
The first two are epidote (with its microcrystalline variety alterite) and hornblende. Since almost the whole southeastern coast of the ria is situated in the coarse-grained postkinematic Caldas granite, we shall have to consider which minerals are supplied by this granite. According to Floor (1968), the most important are epidote (pistacite) and hornblende, with zircon in the fine-grained size grade. Accordingly, the *epidote association* should be considered the association natural to the Caldas granite coasts. The appreciable zircon content of this association is consistent with this view, but the generally low hornblende percentages should be attributed to the low resistance of this mineral to weathering.
The epidote association, however, is found in only some parts of the coast: the section from Villanueva to Cambados, the NW of the Isla de Arosa, and some isolated points scattered along the coasts. In the remaining coastal section this association gives way to other associations.
The *hornblende association* is, according to Koldijk's (1968) findings, typical of the Umia River, which for a considerable part of its lower course runs through the Caldas granite. On the beaches the hornblende association is found directly S of the mouth of the Umia River. Recent supply must be the reason why the hornblende is not yet weathered away here. Isolated cases of high hornblende contents at other localities may also be due to a local supply of fresh hornblende.
In the northern, inner part of the ria there is, however, another source of hornblende: the Ulla River also brings this mineral into the ria (Koldijk, 1968), possibly acquiring it from basic metamorphic rocks farther upstream (Floor, 1968). Hornblende accumulated in the upper part of the ria when the sea level was lower than it is now, and would have been washed ashore, e.g. near Villagarcía, when the sea level rose.
The *tourmaline association*, as already mentioned before, is certainly of local origin. It is confined to Cortegada Island, which consists of two-mica granite. The tourmaline could have been derived either from this rock type or from its pegmatite dikes (Floor, 1968).
The greatest problem is posed by the *metamorphic association*, since this has the widest distribution along the southeastern ria coast, although the geological map shows no outcrops of metamorphic rocks along the coasts from Carril in the N to La Lanzada beach in the S. Yet the hinterland of this coast may contribute to the supply of metamorphic minerals to the beaches.
(a) In the first place, the intrusive Caldas granite contains numerous xenoliths of metamorphic rocks (Bisdom, 1967). The granite is widely covered by colluvium, which is so strongly weathered that only quartz pebbles have been preserved in it. It is likely

that also among the heavy minerals the least weatherable components have been preserved, especially the zircon from the granite and the metamorphic minerals from the xenoliths. This colluvium, partially reworked by waves during the interglacials, is exposed in many places in the cliffs and could thus have supplied metamorphic minerals to the beaches.

(b) Another source of supply, also from the hinterland, are the bedded (torrential) slope deposits S of the Ensenada del Grove, which also supplied the kaolinite to the Ensenada and the adjoining land. These deposits, which originated from the metamorphic area S of the Ensenada and contain high percentages of mainly staurolite and andalusite (Amstelveen, 1965), continue below the sea, and the sand fraction may have been washed ashore during the rise in sea level.

(c) A more important supply, however, may have come from the opposite shore of the ria, which consists partially of crystalline schists. Continuous seismic profiling of the ria bottom (Hinz, 1970) has shown that part of the ria bottom is filled by sedimentary deposits with a thickness of up to 30 m and locally even more.

Part of this material may have been deposited by the Ulla River itself, but a large part was probably supplied by tributaries from the NW (Pannekoek in Hinz, 1970). This is corroborated by the heavy-mineral composition. Part of the northwestern coastal zone consists of andalusite-rich schists, and consequently andalusite is by far the best-represented mineral in the NW beaches of the outer ria. The same holds for the beaches along the SE shore of the outer ria, i.e. the western end of the Peninsula del Grove. It is therefore assumed that the andalusite-rich sands were supplied from the NW into the ria bottom when this area was dry, and then, when the sea level rose again, were washed ashore on both coasts of the outer ria.

More difficult to account for is the dominance of staurolite along the southeastern coast of the inner ria, especially since staurolite is usually a rare mineral on the opposite coast. Staurolite, together with hornblende and epidote, is supplied by the Ulla River (Koldijk, 1968) and thus will occur in the bedded sediments on the ria bottom, especially in the inner parts. From there it may have been supplied, when the sea level rose, to the present beaches, albeit with less hornblende due to weathering.

Since staurolite, according to the current literature, is moderately weatherable, its dominance not only in the beaches but also in the strongly weathered colluvium, is perhaps surprising. One of the present authors (H.H.P.) is inclined to suppose that staurolite is actually less susceptible to weathering than is generally assumed. There are instances where staurolite is found in association with the least weatherable minerals: rutile, zircon, and tourmaline, and also Grimm (1957, p. 171) indicates that staurolite is much less weatherable than andalusite. This assumption would also explain the wide distribution of staurolite in the ria area.

MINERALOGY: LIGHT MINERALS

Quartz/feldspar ratio (Fig. 13)

The light minerals were also determined in the 50—500 micron size grade in 24 samples, according to the method described by Vogel (1965). To avoid attack or solution of the minerals, especially of the feldspars, the samples were washed with water only.

Bisdom (1967, p. 43) has shown that in a weathering profile in granitic rocks the feldspar content is still much higher than the quartz content (Fig. 13, locality B). In the river sands the relative amounts of these minerals have already been reversed (Koldijk, 1968): about 15 km upstream from its mouth the Ulla River shows 64% Qu and 36% Fsp, and at its mouth 71% Qu and 29% Fsp. At the mouth of the Umia River these values are 61% Qu and 39% Fsp.

Quartz/feldspar ratios in the coastal sediments are highly variable although two values occur with a much greater frequency. This is clearly illustrated by the quartz/total feldspar ratios in the beach sands of the El Grove Peninsula:

La Lanzada	3.0
S coast	6.3
W coast	3.8
NW coast	1.0
E coast	1.0
La Toja	1.1
La Toja	0.8

In this distribution the values 3.0—6.3 form one group and the values around 1 another. Similar values are found in the ria. The cuspate spit of El Vado offers the best examples of sands with very high values: 11—14. Cortegada Island and Playa de las Sinas also show moderately high values (about 2.5). In other localities sampled for light-mineral determinations, values of about 1 were found frequently. Some, however, show values of $\frac{1}{2}$, so that feldspar is strongly dominant; such a sample was taken from beach sands apparently directly derived from weathered basement rocks. The high quartz/feldspar ratios along the La Lanzada beach, the S coast of El Grove, and in the El Vado cuspate spit, are in agreement with Díez Taboada's finding (1967) that the quartz content is higher where „marine" influence on sediment is greater.

Carbonate content

According to the results obtained for 60 samples of beach sands, carbonate percentages vary widely: along the LWM from 0.02—28.2, along HWM from 1.3—15.9, and in samples from tombolos and the El Vado spit from 0.3—52.0 The highest carbonate contents were found in samples from beaches with the greatest exposure to rough ria water: the NW point of the Isla

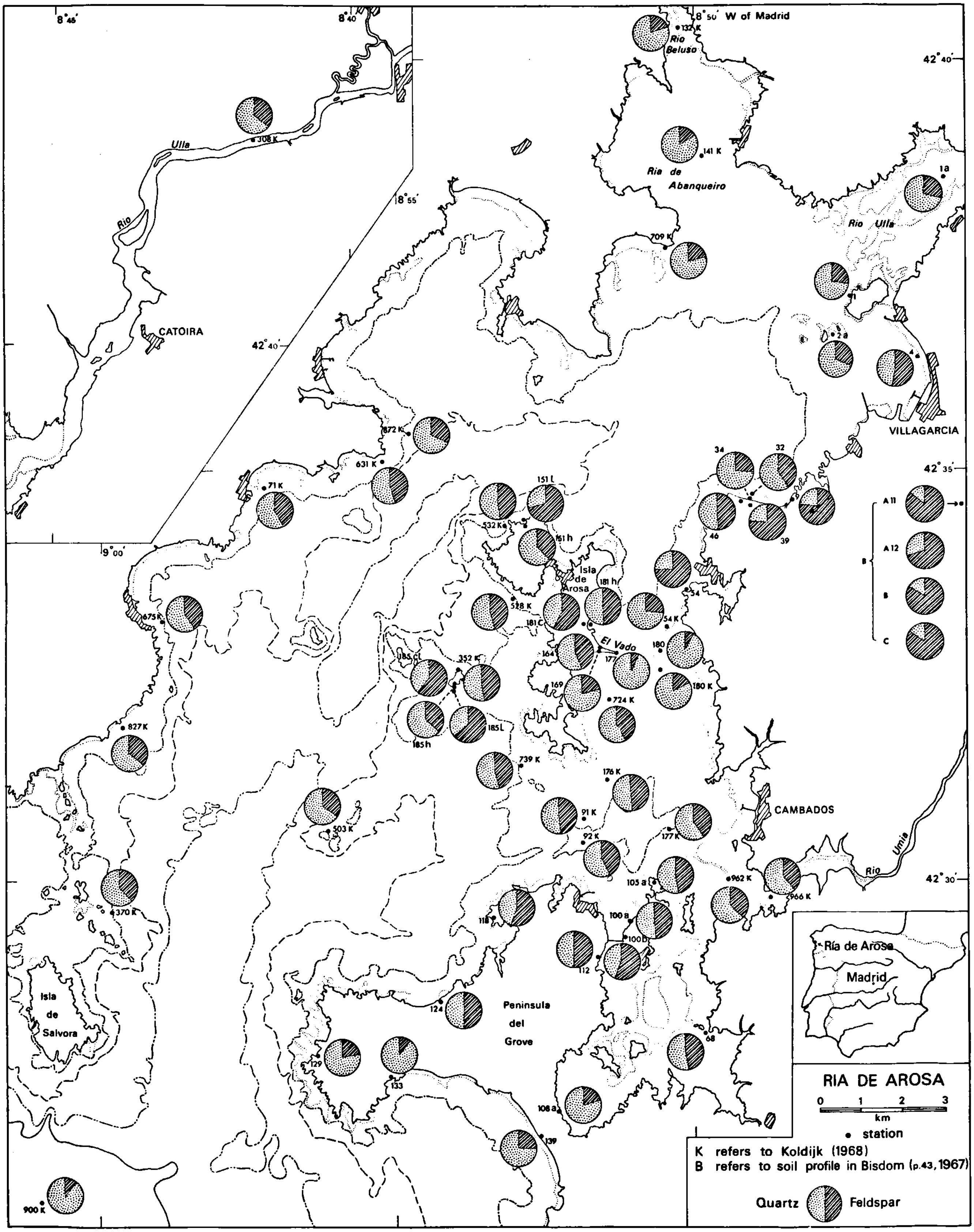


Fig. 13. Quartz/feldspar ratios of the Ría de Arosa (including data from Koldijk, 1968, and Bisdom, 1967). Approximate scale 1:125,000.

de Arosa, the S point of the Isla de Arosa, and the Jidoiro Islands.

CONCLUSIONS

The beaches along the southeastern shore of the Ría de Arosa show great differences in grain size and mineralogical composition. They vary from high-energy beaches along the open ocean and some exposed spots, through beaches moderately exposed to wave action, to protected beaches and, in embayments, even to tidal-flat areas.

These beaches are generally small and separated by low capes, often granite tors; almost entirely submerged tors are also found on the beaches and in the water. Actually, the present coast is nothing more than an accidental line separating a subaerial from a submerged part of a uniform granite topography (Pannekoek, 1966).

A large part of the beach sand is locally derived from the low cliffs along the beaches. Where weathered granite is exposed on the shore it supplies granules to the beaches, which accounts for the coarseness and angularity of many of the beach deposits. But colluvium and older marine terrace deposits also contribute material to the beaches; locally, the terrace deposits have supplied well-rounded pebbles.

The heavy minerals show that the hinterland is not the only source of the beach sands. Epidote, zircon, tourmaline, and part of the hornblende are derived directly from the local bedrock, but the widely distributed metamorphic minerals are more difficult to account for. They may derive partially from hinterland colluvium, which took these minerals from the xenoliths in the granite and became enriched in metamorphic minerals through weathering of epidote and hornblende. However, metamorphic minerals were probably also supplied by the Ulla and its northern tributaries to the bedded sediments on the bottom of the ria (Hinz, 1970), from which they were gradually washed ashore during the interglacial and postglacial rises of the sea level.

The beaches thus clearly reflect parts of the complicated history of the ria.

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