DEPARTMENT OF
MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1974/85

DETERMINING THE DISTRIBUTION AND CLASSIFICATION OF THE BROAD SOUND (QUEENSLAND) SURFICIAL SEDIMENTS USING NUMERICAL TECHNIQUES

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SUMMARY

Four basic sedimentation units can be identified in the Broad Sound surficial sediments using the sedimentation model proposed for the estuary. They can be separated on an X-Y plot of the mean and standard deviation values of the sample grainsize frequency distributions. The geological interpretations of the changes in the mean and standard deviation in each sedimentary unit may be used for detailed study of the sedimentary inter-relationships.

The interpreted geological processes associated with the sedimentary model and the resulting sample classification are supported by the results of a Q-mode factor analysis carried out on variables measured on the Broad Sound samples.

INTRODUCTION

In 1970 and 1971 the Bureau of Mineral Resources undertook detailed field studies of the Holocene sediments of Broad Sound, Queensland. The sedimentation, mineralogy, petrology, geochemistry, and geochronology of the samples were subsequently studied (Cook & Mayo, 1974, in prep.). This paper is concerned primarily with the grainsize studies on the samples collected during the 1970 field season from the shallow marine, open intertidal, mangrove channel, mangrove swamp, and supratidal flat depositional environments.

The most common grainsize parameters used in sedimentological studies are mean, standard deviation, skewness, and kurtosis, as well as percent values of gravel, sand, silt, and clay fractions of the sediment. From these parameters it is often possible to determine the provenance of the sediments or to classify samples into separate depositional groups. When a study requires the unravelling of detailed inter-relationships between variables, grainsize parameters can again be extremely useful.

If the changes in these parameters can be interpreted geologically, the reasons for changes in other variables associated with the grainsize parameters can perhaps also be explained. This concept applied to grainsize parameters as well as other variables is discussed in detail by Griffiths (1963), who was attempting to find the critical properties of oil-bearing sands. This paper will concentrate on the geological interpretations of changes in grainsize parameters, but their usefulness in determining provenance and in grouping the samples will also be discussed. A basic sedimentation model of the Broad Sound system is also presented, as a basis for these discussions.

Four parameters, mean, standard deviation, skewness, and kurtosis, were determined on all samples obtained according to the selected grid pattern and on the mangrove channel samples. The phi ($-\log_2$mm) transformation was used throughout because the grainsize distribution of many sediments tends to become symmetrical when a logarithmic size scale is used (Krumbein & Pettijohn, 1938).

The gravel fraction ($>$2.0 mm; Wentworth classes are used throughout) was sieved, the sand fraction (2.0 to .063 mm) analysed with a settling tube, and the pipette method used for the mud fraction ($<$.063 mm). The samples were not treated with acid before analysis, but organic matter was removed (Armstrong, 1973). Program GRSIZE (Mayo, 1972) was used to combine the results from the three fractions, and output the grainsize distribution parameters, the grainsize frequency distributions, and the percent gravel, sand, mud, silt, and clay. The program uses statistical moment measures (reproduced in Appendix I) to determine the distribution parameters and 3 is subtracted from the initial kurtosis value so that a normal distribution would have a kurtosis of 0. In addition the percent gravel, sand, and mud values were determined on the samples after calcium carbonate had been removed with dilute hydrochloric acid. The percent calcium carbonate in the gravel, sand, and mud fractions was determined theoretically from these percentages together with the average calcium carbonate in each environment.

SAMPLING AND SAMPLE CLASSIFICATION

Sampling Grid - Number of Samples

A map, previously compiled from air photographs, separated the supratidal flat, the mangrove, the open intertidal, and the shallow marine environments of Broad Sound. From this map the number of localities to be sampled from each of these environments could be estimated, given the sampling system and the seaward limit of sampling.

Random sampling of the estuary was considered essential, but as a pilot study had not been carried out, no final decision on all environments to be studied could be made. Sampling at the intersection of a square grid was therefore selected to give random sampling over the whole study area as well as in individual environments. Variables could then be compared between separate environments and the whole estuary. Where necessary, environments not adequately sampled with the selected grid could be sampled separately with any random sampling technique and results could still be compared to those for the total area. The only theoretical problem with the use of such a grid would be that cyclical variation of any of the measured variables on the same scale as the selected grid size would result in biased results for that variable. Cyclical changes were not expected at Broad Sound and this problem was ignored.

A central limit theorem states that if a random variable, x, is distributed with a mean μ and standard deviation σ, then $(\bar{x} - \mu)/(\sqrt{n}/\sigma)$ approaches the standard normal (mean o, standard deviation 1) distribution as n becomes infinite, where $\bar{x}$ is the sample mean of x obtained from n samples (Hoel, 1962). The more the distribution of x departs from normality the larger the number of samples required to ensure approximate normality. Past sampling studies (Hoel, 1962, p. 146) have shown that with a sample number of about 50 the mean of any variable measured on these samples will be approximately normally distributed irrespective of the frequency distribution of that variable. Statistical techniques assuming normality can be used when working with the means of variables measured on this number of samples. Consequently, various sizes of grids were placed over the environment map to vary the number of localities in each of the four environments with the aim of obtaining approximately 50 samples in the environment covering the smallest area.

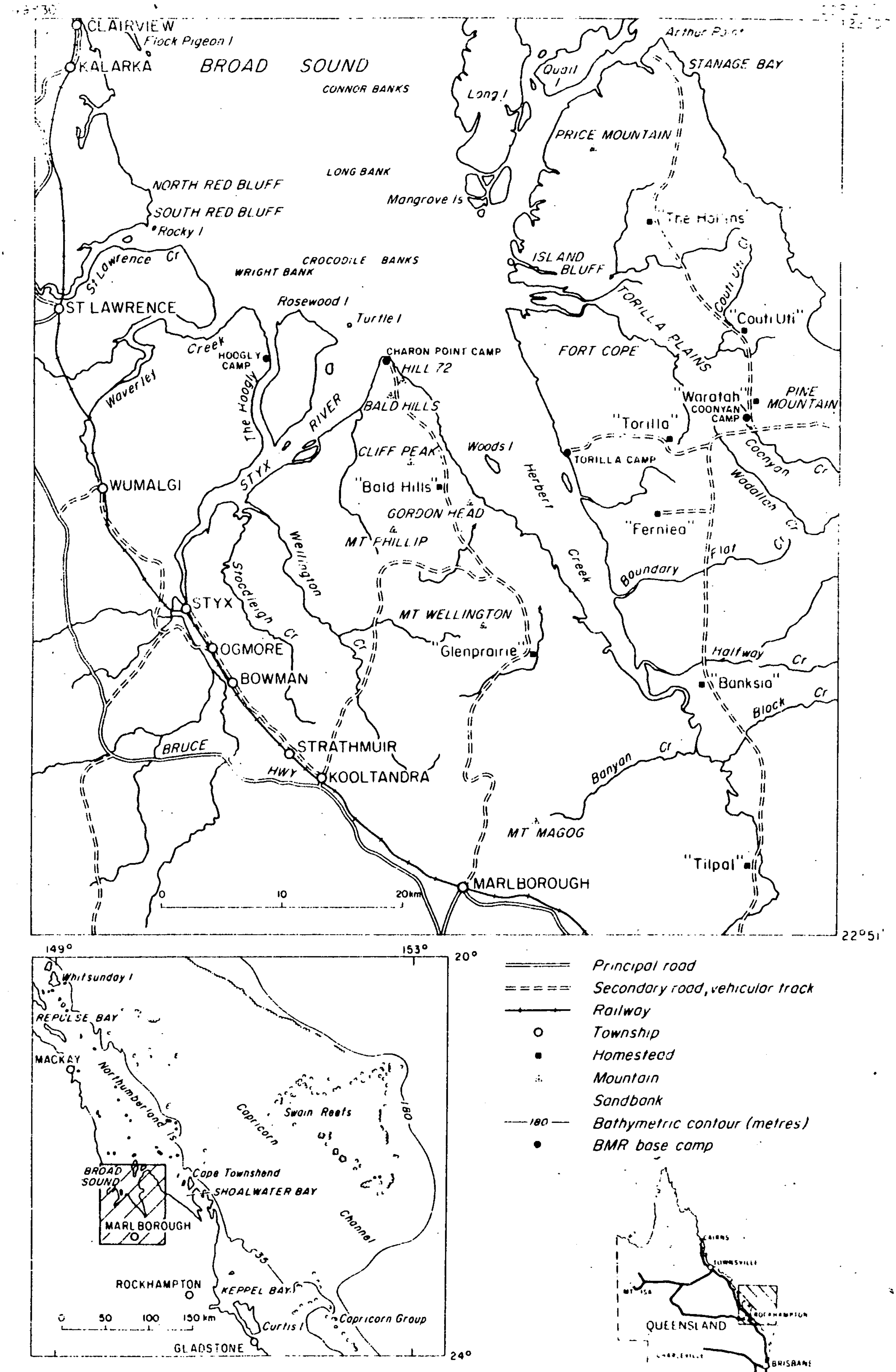
The mangrove swamp environment in the region south of Long Island (Fig. 1) covers the smallest area, and with the grid set at 1.9 km there were 72 sampling localities in the supratidal flats, 59 in the mangrove swamp environment, 97 in the open intertidal environment, and 91 in the shallow marine environment. Therefore with this grid size, adequate sampling of the environment covering the smallest areas would result; further subdivision of the other three environments would also be possible.

The only remaining decision was whether the selected grid should be randomly oriented over the estuary. This problem was solved when just before the field study started 1:100 000 topographic maps of Broad Sound with a 1 km grid became available (Fig. 1). For convenience, this grid at 2 km spacing was used without affecting the randomness of the sampling.

Owing to errors in the original environment map, and changes in the size and position of the final sampling grid, the total number of sampling localities in the mangrove swamp environment was actually only 27. Numerous sampling points interpreted as supratidal flats in fact were coastal grasslands (extratidal) and consequently were not sampled, but the total was still 68. 70 localities were sampled in the shallow marine environment and 105 in the open intertidal. In addition to these grid samples it was decided while in the field to sample the mangrove channel environment separately. This environment was sampled at 2 km intervals by dividing up the total length of all the major channels. Thirty four localities were selected in this way and sampled. Extra samples were taken along the centre of the Waverley and St Lawrence creeks, the Styx River, and the Hoogly, at intersections with the 1 km grid lines. Fig. 1 shows all the estuarine sampling localities; the numbers are indexed in Appendix II.

Environment Classification of Samples

The classification of samples into the five environments is based on field observations and is a 'visual' classification only. Each variable measured on a sediment will probably reflect either the nature of the original source material, processes of deposition, or



To accompany Record No 1974/85 Fig. 1a Locality map. F55/A12/51

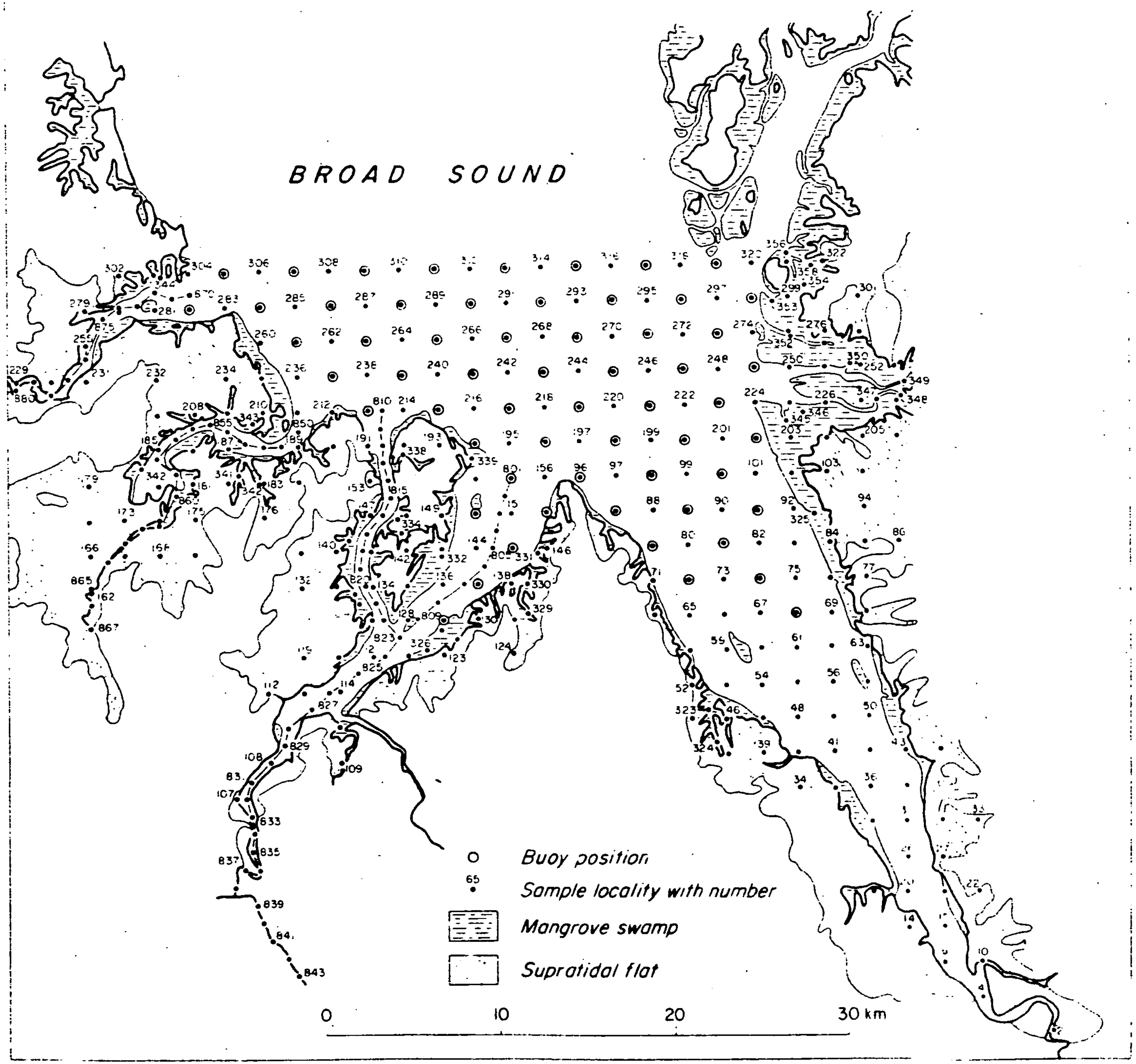


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Fig 11 Broad Sound sampling localities

diagenesis, or combinations of these. A numerical classification of the samples may be obtained by testing differences between values of one variable, or preferably a combination of variables, measured on the sediments. Techniques which may be used include testing the difference between means when dealing with one variable or a discriminate analysis or Q-mode factor analysis with several variables.

A completely different classification may, of course, be obtained by visually and numerically classifying the samples. Perhaps each variable taken separately could lead to a different classification of the samples. Alternatively, changes in each variable over the whole study area could be explained solely by sampling and analytical errors and therefore no classification would be possible.

Despite these difficulties the detailed interrelationships between variables measured on the Broad Sound samples can only be understood by separating the samples into distinct populations. If the samples were not classified the major differences between the populations would mask the details within the individual populations.

Analytical and Sampling Error

An analytical error in measuring any variable, reflects the precision, but not the accuracy, of the analytical technique. Given no analytical error, the value for a variable measured on repeat samples from the same locality would be expected to change because of many factors, the most important being positioning error couples with the local variation of the variable. This error is termed sampling error. Consequently, the combination of the analytical and the sampling errors could be large enough to mask any overall variation in a particular environment. If this is the case that variable should be left out of any numerical analysis.

One-way analysis of variance can be used to test the significance of the combined analytical and sampling error. This is a method for testing the means of several groups simultaneously, each group being repeat samples at individual localities when using the technique for error analysis. If there is no significant difference between the groups of repeat samples for a particular variable, then the combination of errors masks any variation in that variable. The errors can be tested separately using analysis of variance, but in this study the removal of variables with no significant variation (given the analytical techniques used) was the only aim. To make these tests possible, samples were taken in triplicate at approximately every tenth locality sampled in each field environment.

Sampling

Subtidal Zone

Positioning in the subtidal zone can post many problems. It was found by carrying out tests on Lake Burley Griffin in Canberra that a 30 cm square flag on a 2 m pole could be seen with binoculars over about 8 km across water on a clear, calm day. Consequently, it was decided to position buoys at Broad Sound in a diamond pattern spaced as shown on Figure 1: each sampling locality either had a buoy at the position or was marked by the intersection of two lines of buoys at right angles.

This technique worked very successfully to sample the shallow marine environment and some of the intertidal environment, as an observer on board a boat with binoculars was able to see two and frequently three flags in line.

Using these buoys, it was only necessary to carry out this somewhat tedious positioning technique at about half the marine sampling localities. In addition, the buoys were used for positioning when obtaining echo sounder and seismic records as well as coring and water sampling at selected localities.

The buoys were placed using two theodolites at known land positions, each set at the theoretical angle from grid north to the unknown buoy position. By walkie-talkie radio, positioning instructions were sent from each theodolite position to the boat laying the buoys. The greatest positioning error with this method was that in positioning the theodolites on the ground to correspond to the point on the map from which the angles to the buoys were determined. In some positions this could have been as much as 50 m. Error caused by boat movements after final positioning could have been in the order of 10 m. Before each buoy was released the length of rope needed to allow for the tidal range was determined approximately. These lengths were found to be adequate except at half tide during the spring tides, when some flags would be pulled below the surface by the tidal currents.

The rope lengths would also add to the positioning error during sampling, depending on the direction and height of the tide. Small cone dredges with detachable sampling bags were used to sample the marine environment, and boat movement together with the time taken for the dredge to reach bottom could add 30 m to the positioning error.

Taking the worst case, where all the errors are additive, the difference between the sample locality on the map and the actual sampling position could be about 100 m. This positioning error does not affect the randomness of the sampling, and as the repeat sampling was done after repositioning, the tests for error significance will include this error.

Intertidal Zone

Positioning in this zone was as for the subtidal zone when it was possible to make use of the buoys at flood tide. For other localities positioning was carried out using bearings to at least two known landmarks or direct from aerial photographs whether at flood or low tide.

At flood tide cone dredges were again used and the boat repositioned for repeat samples. All but 33 of the intertidal samples were collected in this way. A shovel was used if the locality was sampled at low tide and repeats were then taken without repositioning. Therefore, the sampling error only includes a positioning component when the repeat sampling was done at high tide.

Supratidal Zone

The sampling technique with both the mangrove and the mudflat environments was the same. Positioning was done using aerial photographs and topographic maps with a combination of prismatic compass bearings and pacing. Sampling was done by taking a channel sample from the surface to a depth of between 20 and 30 cm. The random triplicate sampling was carried out without repositioning, the samples being within about 10 m of each other. Therefore the sampling error in both these environments reflects mainly the local variation in the sediment. The mangrove channel environment was always sampled at high tide for convenience, and again the small cone dredges were used, with positioning by aerial photographs.

GENERAL OBSERVATIONS

A summary of all the relevant grainsize results for individual environments and the total estuary is given in Table 1. Owing to missed analyses, 289 (originally 305) samples were used to compile the statistics for this table, 256 from the original grid and 33 mangrove channel samples. From this table many general observations concerning the distribution of the sediments can be made.

TABLE 1 - GRAINSIZE AND CARBONATE STATISTICS

		Shallow Marine (63)	Open Intertidal (100)	Mangrove channel (33)	Mangrove Swamp (27)	Supratidal flat (66)	Total (mangrove channel excluded) (256)
	Mean Grainsize	2.23 (2.16)	3.55 (1.76)	6.62 (1.70)	7.85 (1.07)	8.62 (0.96)	5.06 (3.09)
	Grainsize Standard deviation	2.60 (1.37)	1.31 (1.03)	2.93 (0.98)	2.81 (0.34)	2.73 (0.43)	2.15 (1.18)
	Grainsize skewness	-0.12 (1.33)	0.63 (1.80)	0.46 (1.25)	0.25 (0.49)	-0.19 (0.33)	0.19 (1.37)
	Grainsize kurtosis	1.74 (4.83)	4.99 (8.50)	1.25 (5.85)	-0.92 (0.93)	-0.85 (0.35)	2.06 (6.36)
	Number with gravel component	53	20	8	0	4	77
$CaCO_3$ not removed	(%Gravel	18.9	1.9	1.4	0.0	0.2	5.5
	(%Sand	62.1	80.4	27.3	8.6	4.2	48.7
	(%Mud	19.0	17.6	71.3	91.4	95.5	45.8
	(%Silt	9.1	9.7	30.0	38.7	29.8	17.8
	(%Clay	9.9	7.9	41.3	52.7	65.8	28.0
	Number with gravel component	33	12	9	0	9	54
$CaCO_3$ removed	(%Gravel	1.7	0.9	0.9	0.0	0.4	0.9
	(%Sand	64.6	71.3	13.4	2.2	3.7	44.9
	(%Mud	33.7	27.9	85.7	97.6	95.6	54.2
	% $CaCO_3$	56.5	31.3	23.4	16.5	4.3	29.0
	% $CaCO_3$ in gravel fraction	96	67	51			
	sand fraction	55	37	62	79	10	
	mud fraction	22	0	8	3	3	

Summary of all grainsize parameters plus other relevant statistics. Values are the means unless otherwise stated. Standard deviation values are given in brackets.

Grainsize increases seawards from the supratidal flats, through to the shallow marine (also referred to as 'marine' later) environment (Fig. 2). Generally, increasing grainsize (decreasing phi values) reflects increasing gravel and sand and decreasing mud content (Fig. 3). As gravel content increases sand usually decreases correspondingly, and so with mean values less than 2 phi, increasing grainsize corresponds to decreasing sand content. The grainsize standard deviation of the open intertidal environment is on average much less than of the other four environments (Fig. 4). Samples in the marine and supratidal flat environments tend to have negative skewness, whereas the skewness of the other samples tends to be positive. Kurtosis values are generally negative in the mangrove swamp and supratidal flat environments and positive elsewhere. The spread of each of the four distribution parameter values in the mangrove swamp and supratidal flat environments is much less than in the other environments.

The frequency distribution of the values of each of these four grainsize distributions parameters for the total estuary (256 grid samples) is shown in Figure 5. The distribution of the mean grainsize values shows two dominant modes at approximately 3 phi and 9 phi; the standard deviation plot also has 2 modes at about 0.5 and 2.5 phi units. This suggests that these two measures may be useful in classifying the samples and that this classification could be into two major groupings. Both the skewness and kurtosis distributions have only one major mode centring on the zero value, suggesting that these two parameters may not be very sensitive in distinguishing samples deposited in different environmental conditions.

For samples without acid treatment, high mud, low sand, and zero gravel in the mangrove swamp and supratidal flat environments contrasts with high sand and gravel and low mud in the marine and open intertidal environments. In the mangrove channel environment, gravel, sand, and mud percentages are intermediate between these two groups, but the mud fraction is dominant. Frequency distributions of the percent mud and sand again illustrate the grouping of the samples into two main populations (Fig. 6): one with zero mud and high sand content; the other with about 100 percent mud and zero sand.

Analyses carried out after removal of the calcium carbonate show that most of the gravel in the marine and intertidal environments consists of shells and calcareous nodules. The gravel in the few samples in the supratidal flat environment is terrigenous non-calcareous material washed in from nearby land. Although some of this gravel is transported into the mangrove channels and combined with

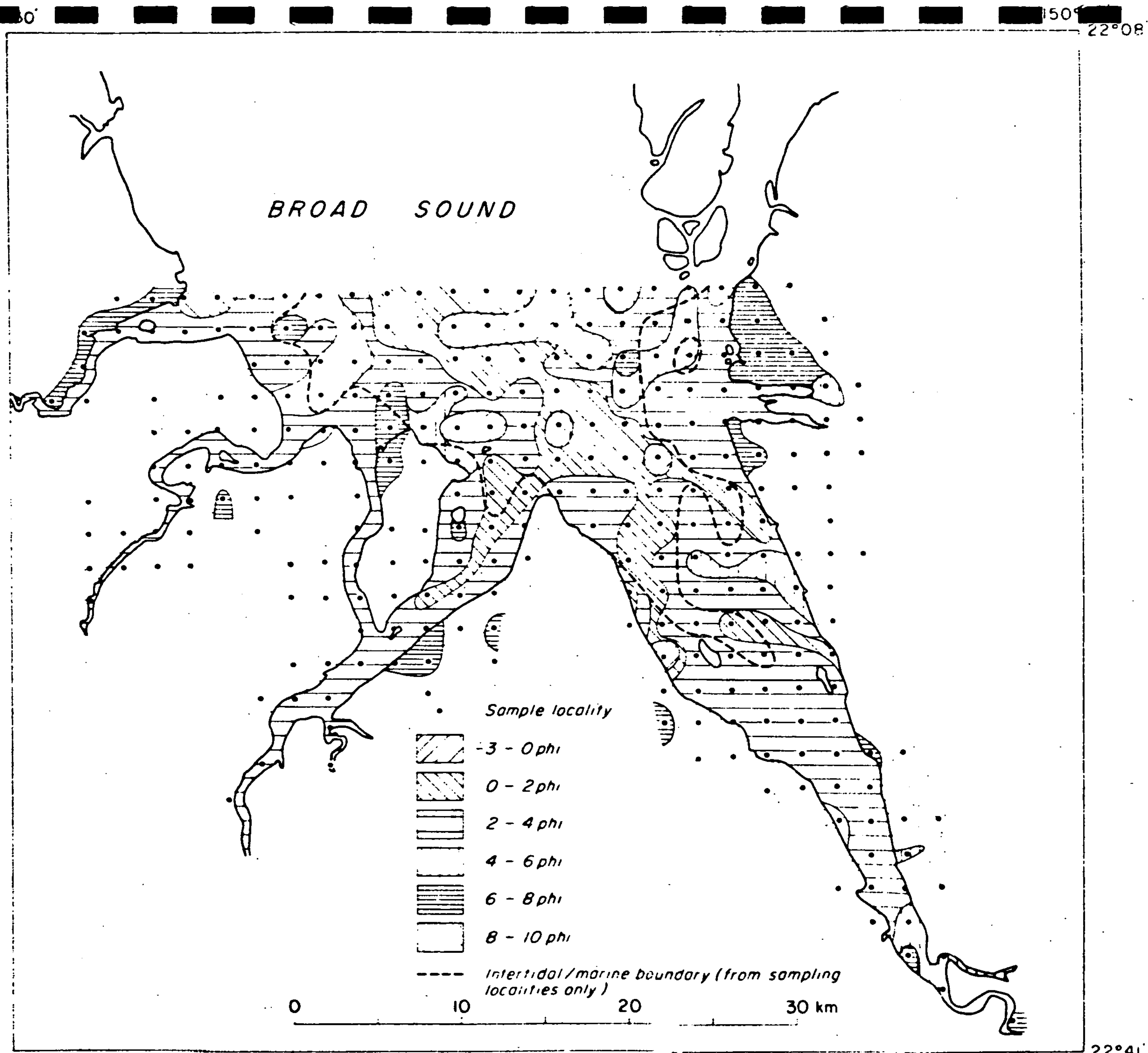

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Fig 2 Areal dist··· ition of mean grainsize values

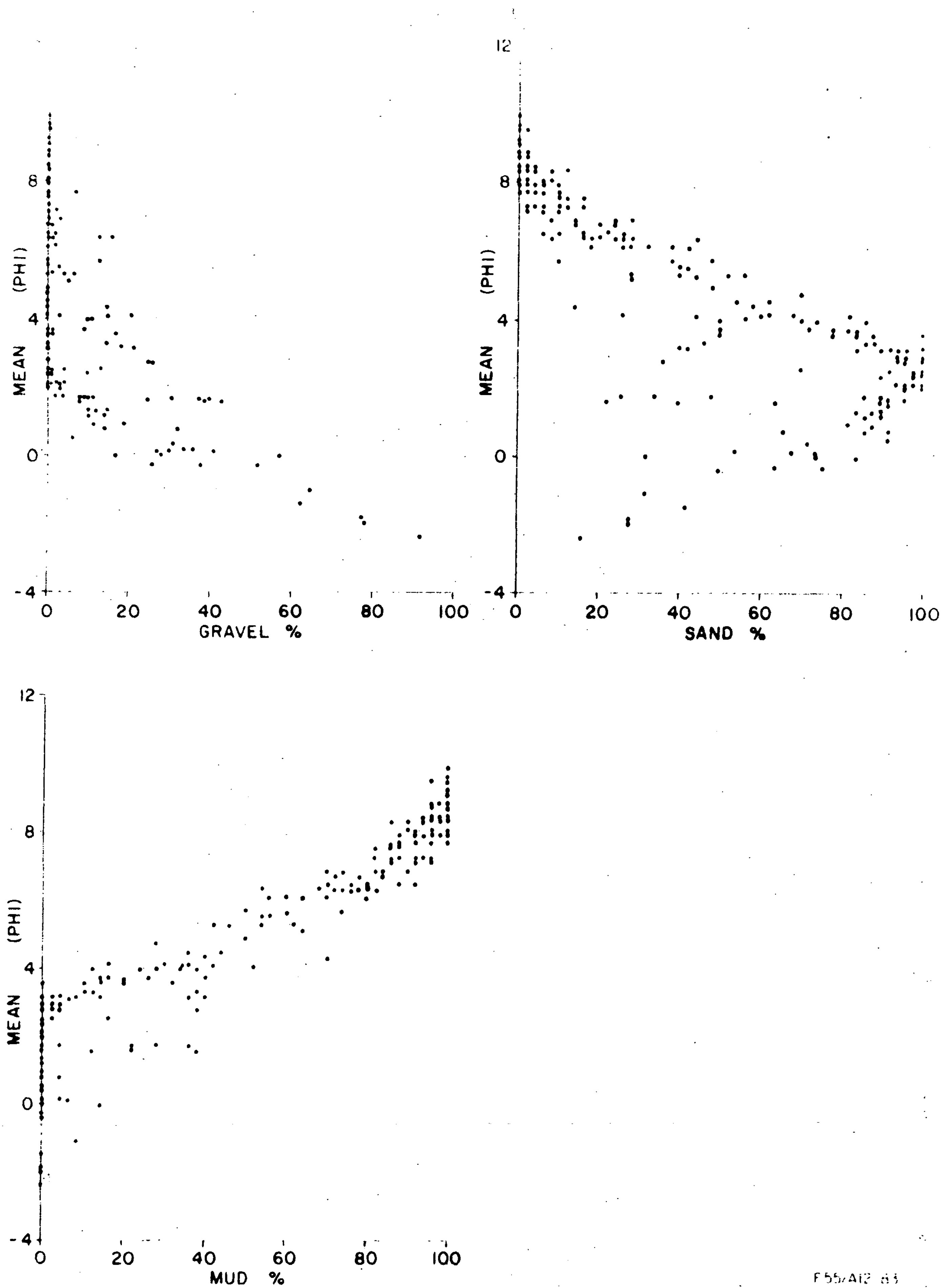

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Fig 3 Relationship between mean grainsize and gravel, sand and mud percent.

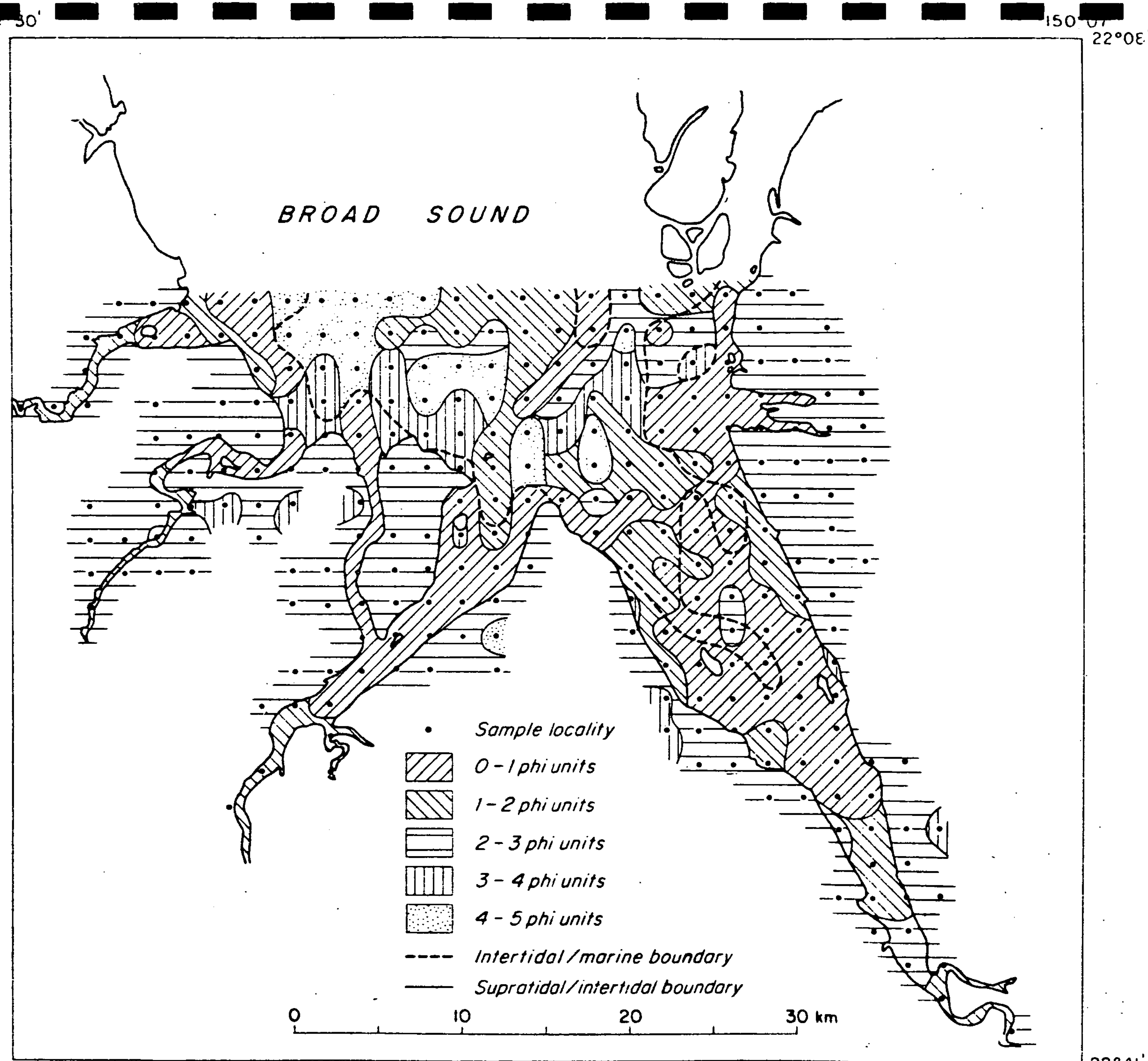

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Fig. 4 Areal distribution of grainsize standard deviation values.

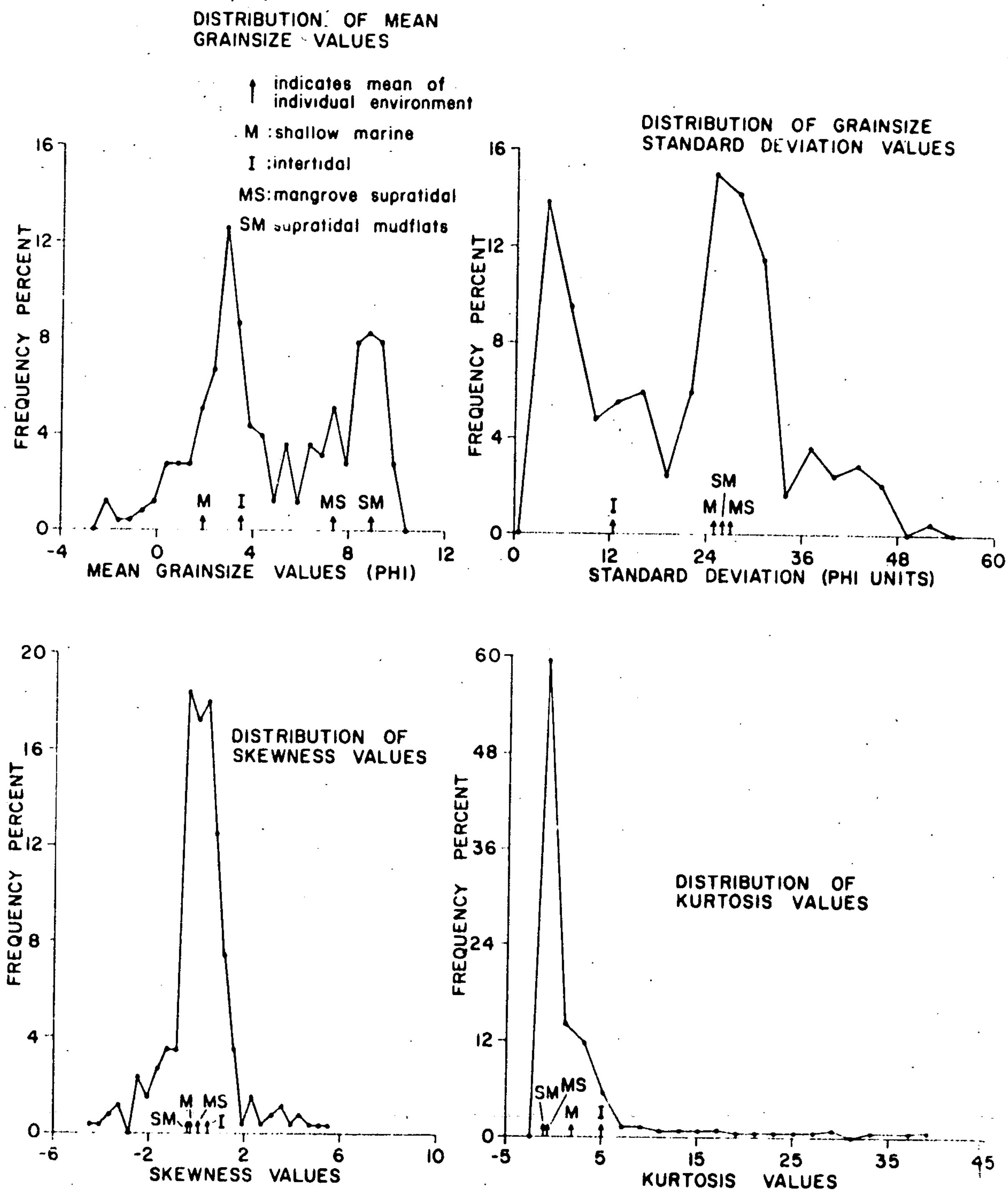

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Fig. 5 Frequency distribution of the four grainsize parameters.

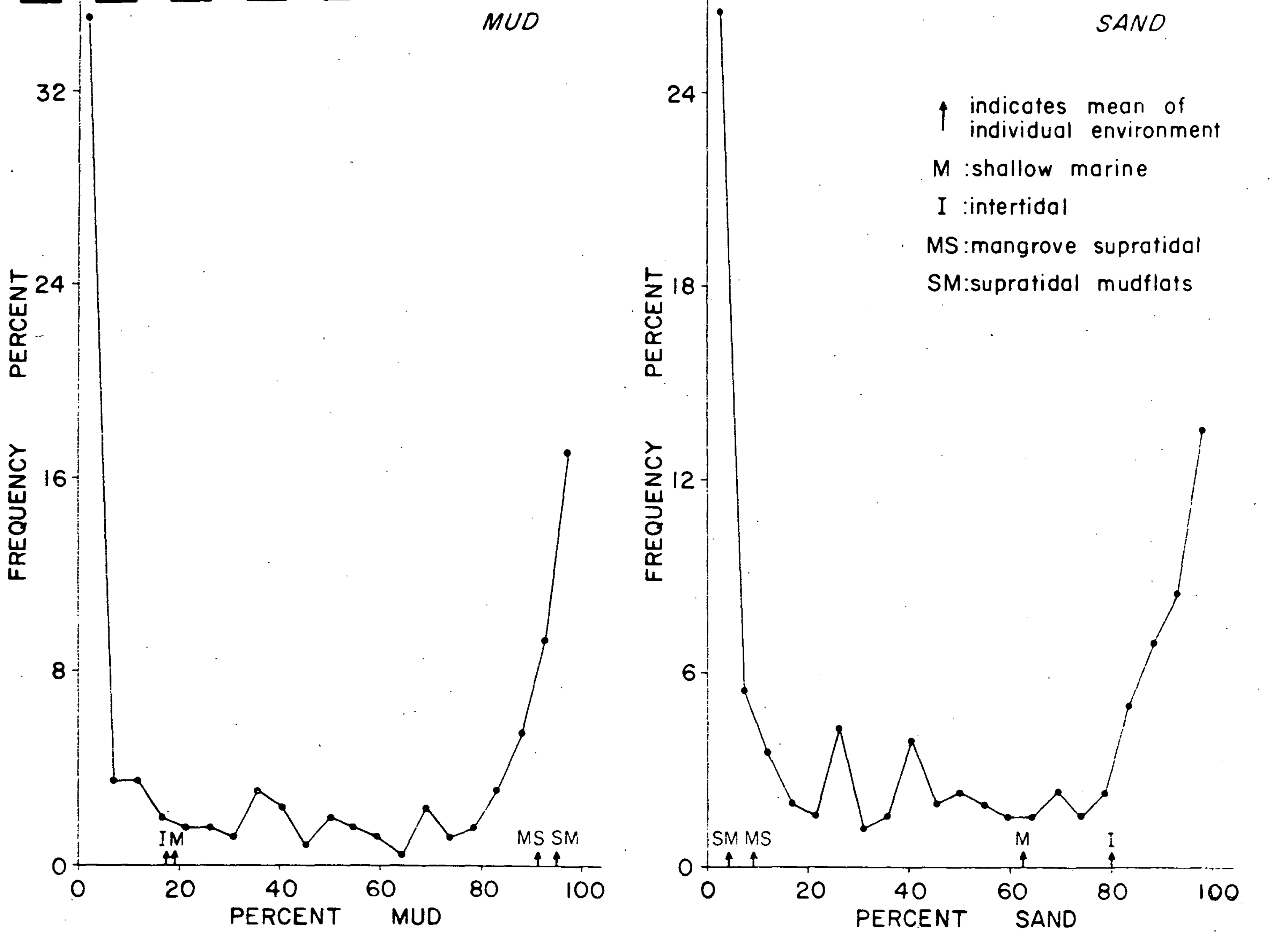

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Fig. 6 Frequency distribution of the percent mud and percent sand values.

calcareous gravel none reaches the mangrove swamp environment. The increase in the number of samples with a gravel component when carbonate is removed, in both the mangrove channel and mangrove environments, is due to splitting error, the carbonate being removed from a separate split.

All environments except the supratidal flats have a high proportion of carbonate in the sand fraction. Where mean grainsize values of the sand fraction with both carbonate removed and not removed were available, the difference between the two was calculated (mean with carbonate subtracted from the mean without). The mean and standard deviation of these differences for each environment is shown in Table 2; their significance can be tested using either a normal distribution test (Hoel, 1962, p. 145) or a Students + distribution test (Hoel, 1962, p. 271), depending on the number of samples used in the test. The resulting distribution values indicate that the mean of the differences is significantly greater than zero only in the shallow marine and open intertidal environments.

As the sand fraction was analysed by settling tube, which measures hydraulic equivalent sizes rather than grain dimensions, the result may indicate that a significant amount of carbonate in the coarse aed of the sand fraction is not in equilibrium with the depositional conditions. This coarse carbonate probably represents the in situ shells and nodules in these environments. From a study of the frequency distributions of the non-carbonate sand fraction in samples from the marine and intertidal environments it was evident that most of this in situ carbonate is coarser than approximately 2 phi. Examples are illustrated in Figures 14(b) and 15(a).

Only a small percentage of the mud fraction in each environment is carbonate, the highest being 22 percent in the marine environment (Table 1). In contrast, the average percent carbonate in the mud fraction of the open intertidal environment is close to zero. This may indicate a winnowing of the carbonate particles (perhaps silt-sized platy shell fragments) from this environment, and that depositing currents are generally stronger in the open intertidal environment than the shallow marine environment. This suggestion on the type of carbonate mud is supported by the carbonate mud content in the other environments. A high proportion of these silt-sized particles would be expected to enter the mangrove swamp environment but would be quickly deposited in the low-energy conditions there, so that only a small amount would remain in the currents flowing through onto the supratidal flats. Although the average energy of the currents in the mangrove channels is probably between that of the open intertidal and the mangrove swamp environments, much of the carbonate silt transported along the channels during flood tide would be washed out again during the ebb.

TABLE 2 - SAND FRACTION STATISTICS

	Shallow marine	Open intertidal	Mangrove channel	Mangrove swamp	Supratidal flats
Number of samples with mean grain-size value for the sand fraction	69	99	17	3	10
Mean of difference between sand means ($CaCO_3$ in and out)	.648	.079	-.225	.127	.067
Standard deviation of differences	.640	.215	.606	.100	.37
Normal distribution value Student + distribution value	8.41	3.65	-1.4	1.8	.54
95% two-sided critical value	1.96	1.96	-2.12	4.30	2.26

	Sand fraction	Shallow marine	Open intertidal	Mangrove channel	Mangrove swamp	Supratidal flats
$CaCO_3$ in	Mean grainsize	1.80	2.92	2.63		2.34
	Standard deviation	.72	.54	0.72		.55
$CaCO_3$ out	Mean grainsize	2.44	3.00	2.41		2.41
	Standard deviation	.44	.54	1.11		.54

% of samples with dominant mode in sand fraction range:	Shallow marine	Open intertidal
2 - 3 phi	86	63
3.5 phi	7	31
1.5 phi	7	6

BED-LOAD TRANSPORTATION

A more detailed study of the size distribution of the non-carbonate sand in the sub-tidal and intertidal zones could be useful in the recognition of the provenance of the sediments. Both the marine and intertidal samples have three important sand fraction modes. These lie at less than 1.5 phi; between 2 and 3 phi; and greater than 3.5 phi. Although individual samples sometimes have more than one mode most have only one. The percentages of the samples in the shallow marine and open intertidal environments with the dominant mode in each of the three groups is shown in Table 2. Combining both these environments, 72 percent of the samples have a dominant sand mode between 2 and 3 phi, and 21 percent have a mode greater than 3.5 phi. Some typical distributions of the non-carbonate sand fraction in the marine and intertidal zones are shown in Figures 7a,b. The main difference between the two environments is the larger proportion of sand particles less than 2 phi in the marine environment.

The areal distribution of these marine and intertidal samples with one mode greater than 3.5 phi, and also those with both the 2 to 3 phi mode and the greater than 3.5 phi mode represented, are shown in Figure 8. These same groupings are also applied to the samples taken down the centre of the Styx River, the Hoogly, and St Lawrence and Waverley creeks and are shown on the same figure: the trend seems to be from 3.5 phi unimodal distribution in the upper reaches, through bimodal to 2-3 phi unimodal distribution at the mouths. This sequence is shown clearly in Figure 9a-d in the series of samples taken down the centre of the Styx River. These samples had the calcium carbonate removed before analysis and the figures shown represent the grainsize frequency distribution of the total sample.

It appears that the predominantly very fine to coarse silt bed load in the upper reaches is selectively removed as the sediments are transported down river so that eventually only the particles in the 2 to 3 phi range remain. This selectively removed material, together with previously suspended silt and clay particles forms a sediments mass oscillating with the tides, but is eventually probably either washed out to sea, or redeposited in the shallow marine or supratidal flat environments. Samples have a dominant mode greater than 3.5 phi because this sorting process has not yet removed the silt and clay particles.

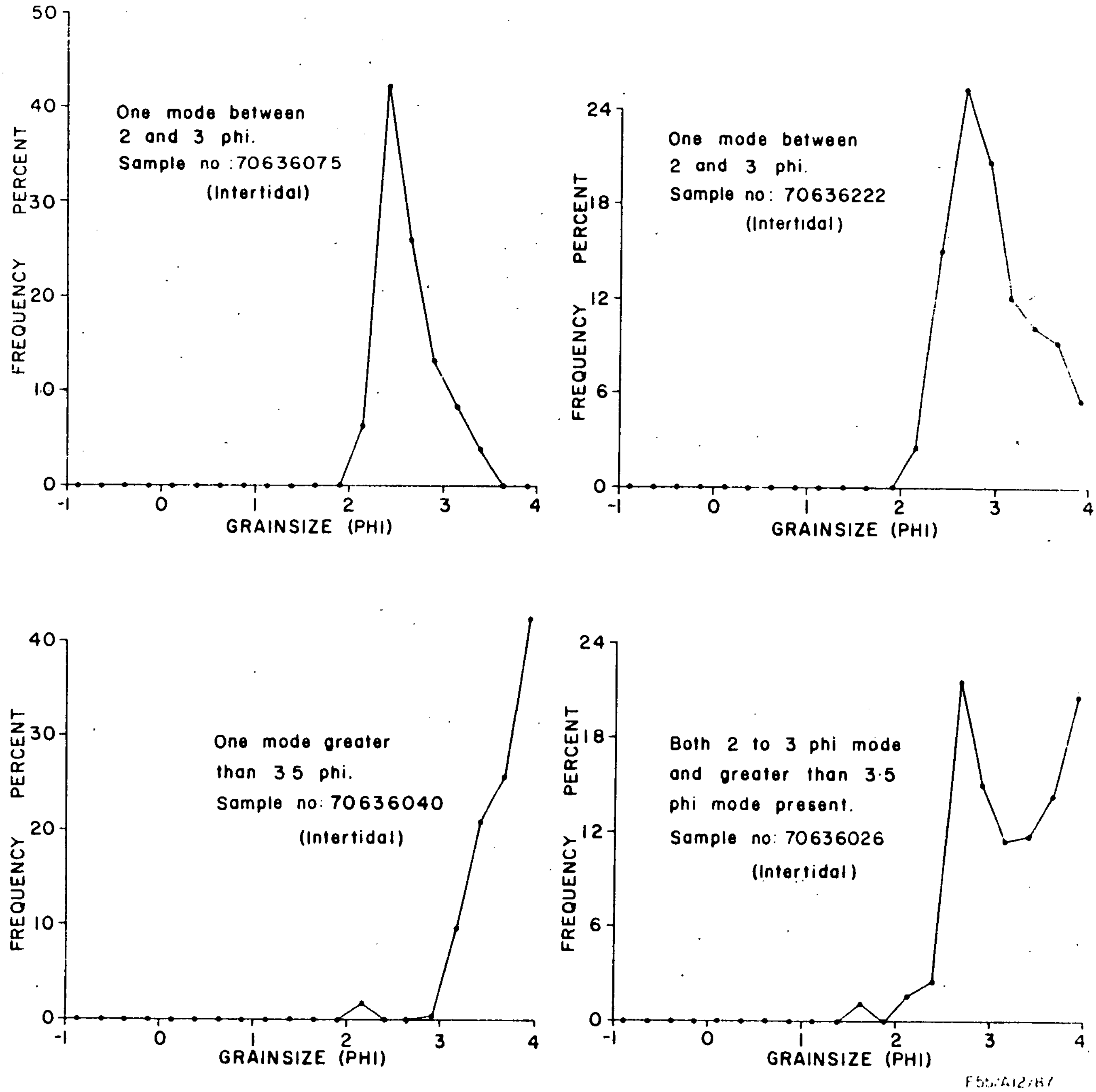

Fig. 7a Typical grainsize distributions of the non-carbonate sand fraction in the intertidal zones.

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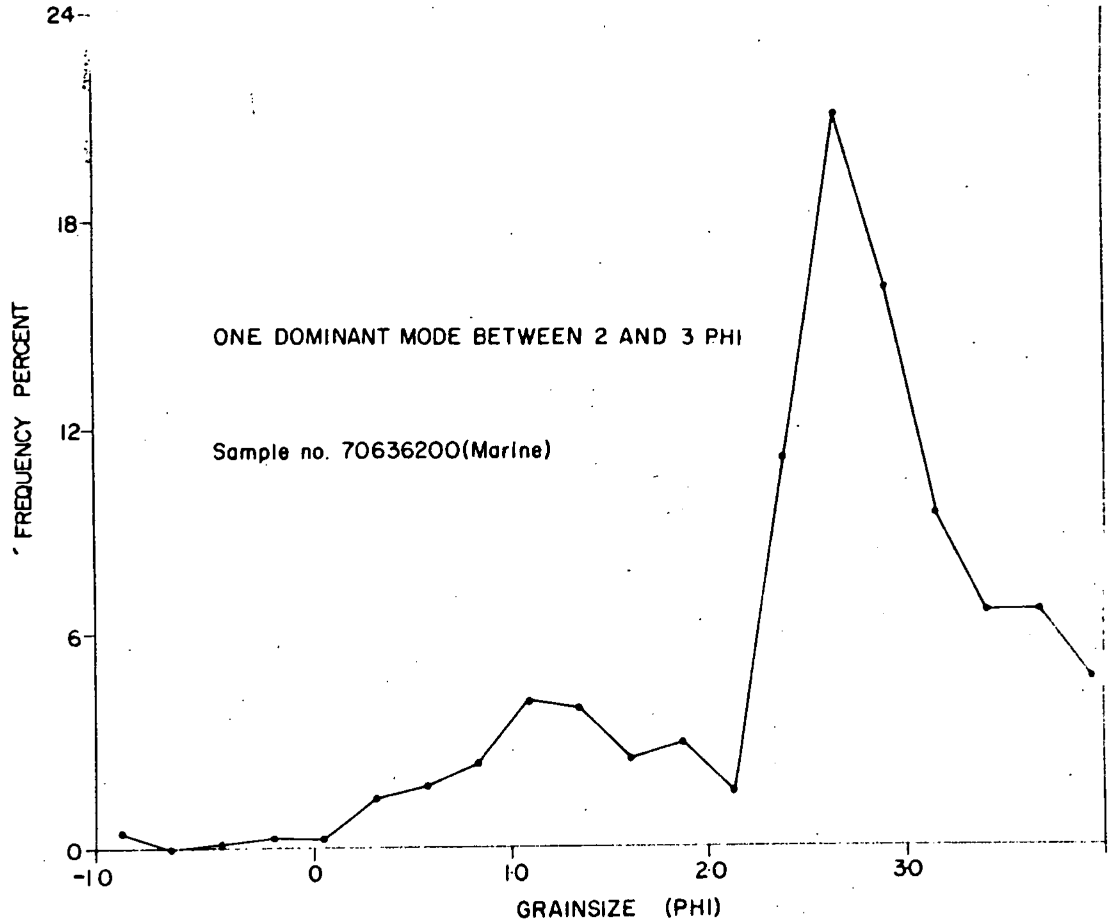

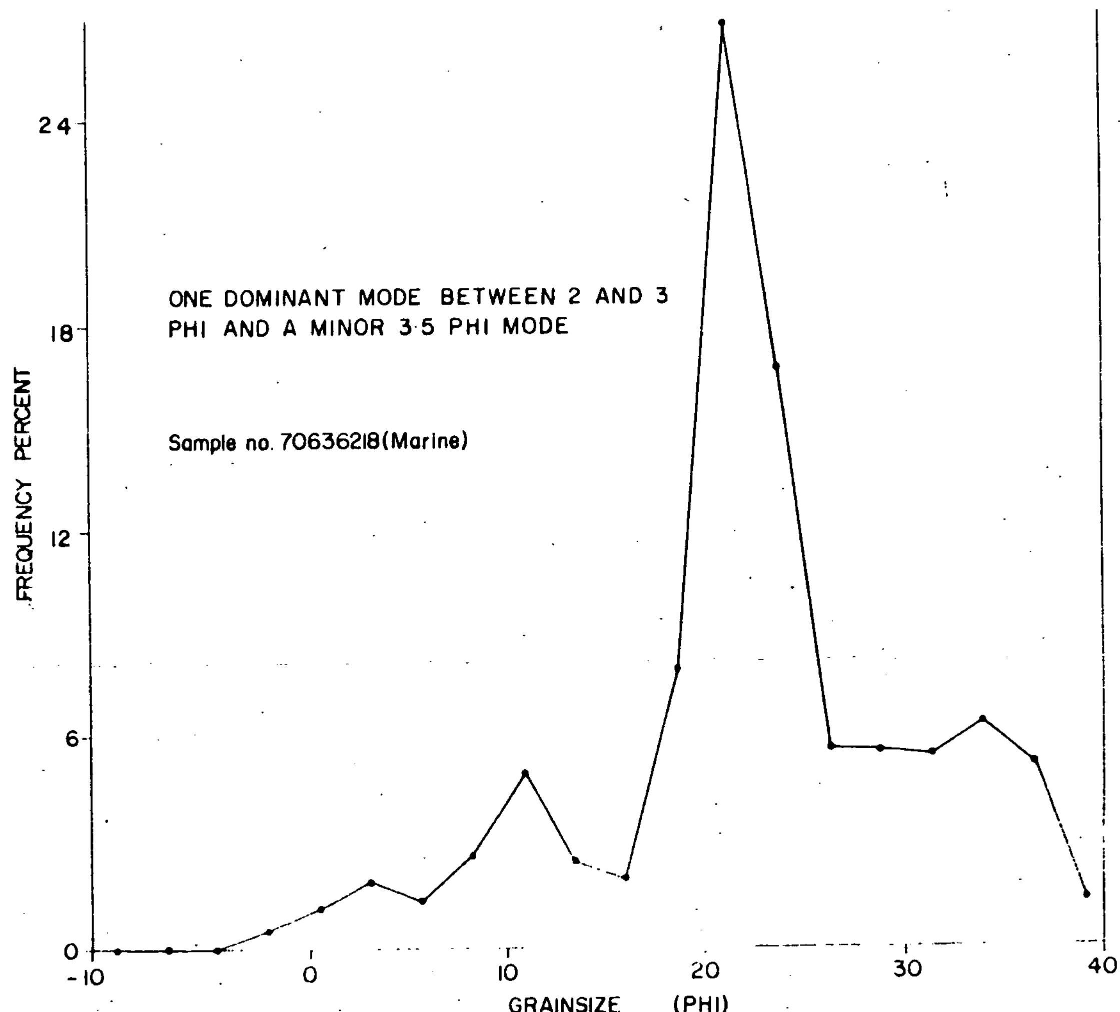

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Fig. 7b Typical grainsize distributions of the non-carbonate sand fraction in the marine zones

The mangrove channels are another major source of supply of terrigenous material. A check on the non-carbonate sand fraction in this environment showed that the dominant sand mode of most samples was in the greater than 3.5 phi category, with some in the less than 1.5 phi group. Although the sediment transported down the channels consists of material washed directly into them from the catchment as well as reworked supratidal deposits the same sorting process may also be applied to it.

This sorting mechanism explains the predominance of the sand in the 2 to 3 phi range in both the marine and intertidal environments. Samples with a dominant mode greater than 3.5 phi are in a pre-sorting stage. The distribution of the non-carbonate gravel fraction shown in Figure 8, and the paucity of intertidal and marine samples with a dominant sand mode less than 1.5 phi, also help in an overall appreciation of sediment movement in Broad Sound. Non-carbonate gravel is fairly common in the supratidal flat and mangrove channel environments, the open marine environment, and the outer reaches of the open intertidal environment, whereas no gravel occurs in the upper reaches of the creeks and rivers. Although most of the gravel in the intertidal and marine environments is probably relict (Cook & Mayo, 1974, in prep.), some may be transported into these zones from the mangrove channels and, presumably, the creeks and rivers entering Broad Sound. The distribution of the gravel could indicate preferential seaward movement of the selectively sorted 2 to 3 phi bodies of sand dominating any movement of gravel and coarse sand and the underlying relict sediments.

So far the assumption has been that the non-carbonate fraction of the bed-load has a net seaward movement, but the gravel distribution and the grainsize frequency distributions of the series of Styx samples could perhaps also be explained by landward sand bed-load movement with relict gravel in the shallow marine zone and preferential deposition of silt and clay in the upper reaches of the creeks and rivers.

The decreasing carbonate content from the shallow marine through to the mud flat environment (Table 1) also suggests a landward movement, but a high degree of intermixing of marine sediments with any incoming terrigenous material would be expected, given the prevailing tidal action. With only small average river discharge and high tidal velocities the proportions of inflow and outflow for both the ebb and flood tides are nearly equal at all depths (vertically mixed estuary). This, coupled with the fact that, with some local exceptions, the ebb tide is stronger than the flood tide (Cook & Mayo, 1974, in prep.), indicates that a net seaward movement of terrigenous sediment is expected together with intermixing of marine sediments.

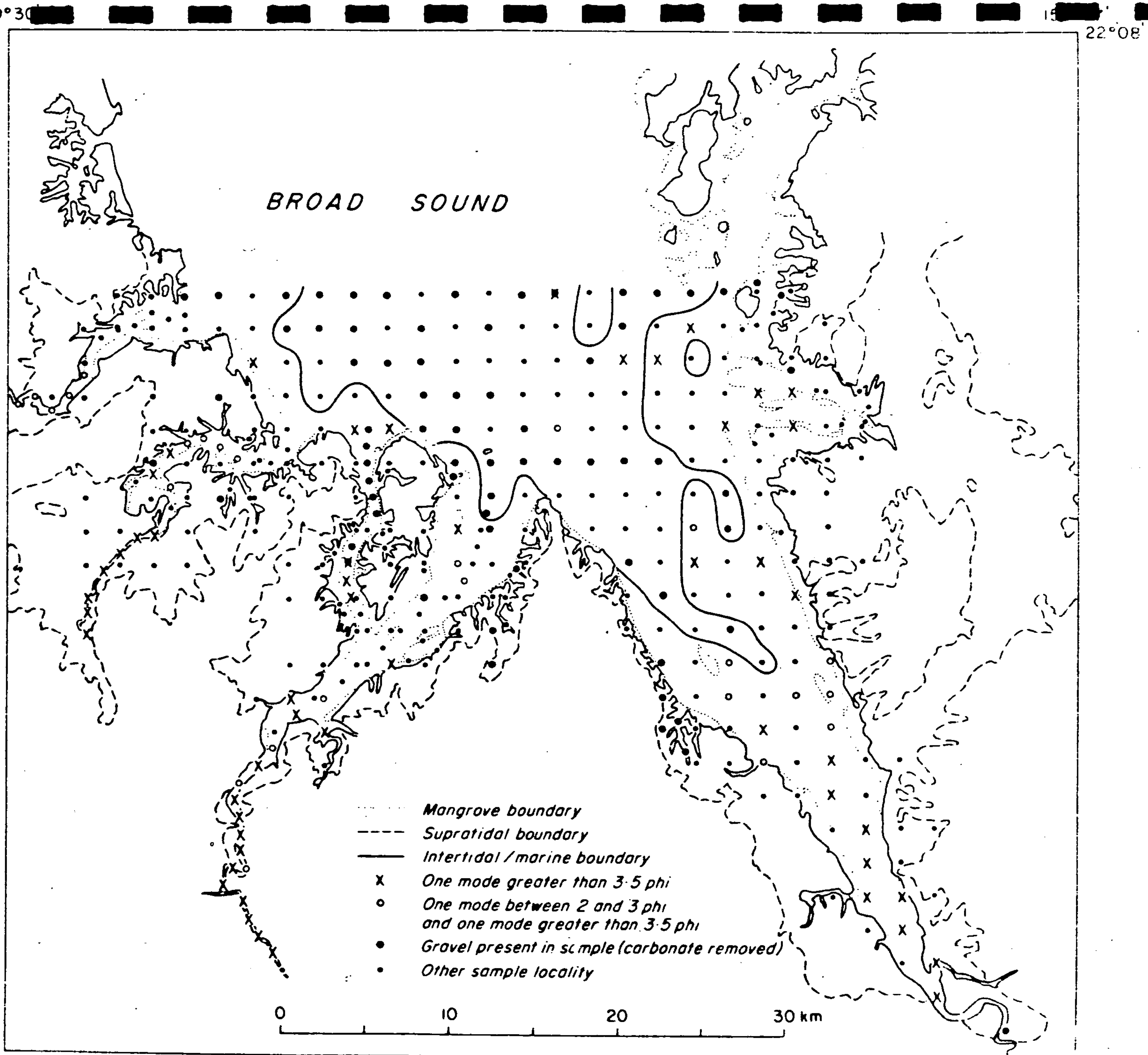

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Fig 8 Areal distribution of the non-carbonate gravel fraction plus the mode positions in the non carbonate sand fraction

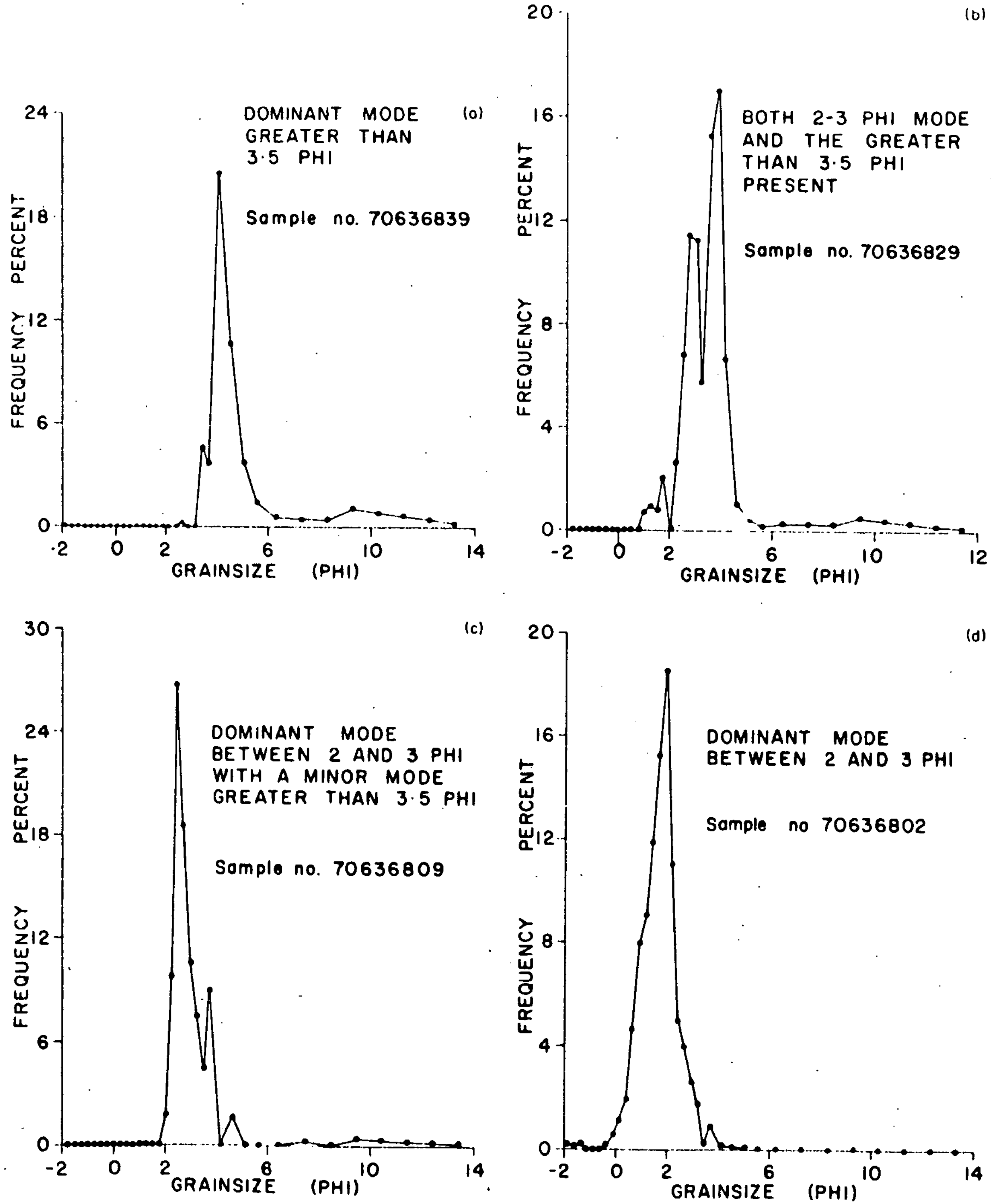

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Fig. 9 Series of grainsize distributions down the centre of the Styx River.

Therefore, the amount of non-carbonate marine-derived material mixed with the locally-derived terrigenous sediments would depend on the available supply of marine non-carbonate material. The sediments of the inner shelf zone seaward of Broad Sound are of a 'non-mud' (about 1 percent mud) facies containing 60 to 80 percent calcium carbonate dominated by molluscs and bryozoans (Maxwell, 1968). The carbonate content increases to greater than 80 percent farther seaward around the shelf reef complexes, so the amount of marine-derived non-carbonate material (especially mud particles) in the estuary is perhaps negligible. Conversely, ample quantities of sand-sized quartz and feldspar particles were observed in the upper reaches of the tributaries supplying sediment to the estuary.

The hypothesis of seaward non-carbonate bed-load transportation is further supported by differences in the degree of mineralogical maturity of the open intertidal and shallow marine sediments. A plot of the ratio of the quartz to feldspar peak areas (the major peaks were used with the feldspars and the peak with quartz) from x-ray diffraction is shown in Figure 10. Although there is a broad increasing trend seaward the result is not conclusive because the trend could be explained either by the landward movement of mature sediments or quite rapid breakdown of the terrigenous feldspar under the high-energy conditions in the estuary.

A plot of the ratio (ZTR index) of zircon plus tourmaline plus rutile to the heavy minerals less resistant to abrasion helps to clarify the issue (Fig. 11). Except for some local variations this ratio is less than 0.25 from the upper reaches to the mouths of the creeks and rivers, but increases to greater than 1.0 (with a maximum of 18.5) seawards. This distribution may reflect the seaward concentration of relict mature sediments, which in turn reflects the effect of the suggested preferential seaward movement of the 2-3 phi sand bodies. Increasing values of the ratio towards the mouth of Herbert creek points to a seaward maturing (mineralogically) of the Holocene sediments in the high-energy intertidal zone. This ratio then supports the idea that bed-load is carried seaward, and this conclusion in turn points to the fact that the feldspar particles in the bed-load are rapidly reduced in the intertidal zone to silt-sized particles which may then be redeposited elsewhere in the estuary.

This type of estuary sediment transportation contrasts that indicated by Meade (1969) and Reinson (1974, in press). These authors indicate that with increasing river discharge a two-layer circulation may develop so that suspended matter is moved seaward but the bottom sediments

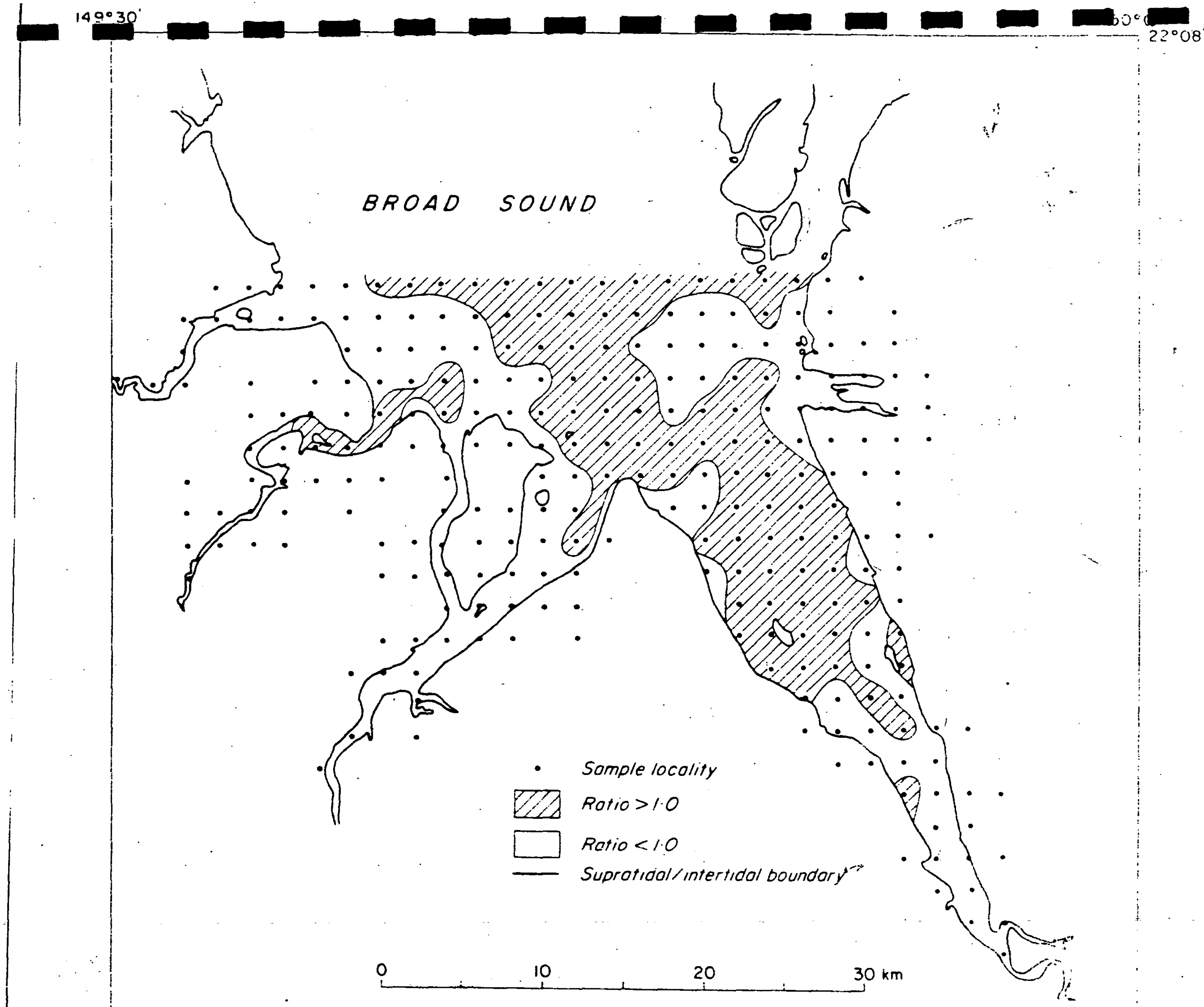

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Fig 10 Ratio of quartz to orthoclase and plagioclase x-ray diffraction peak areas Broad Sound

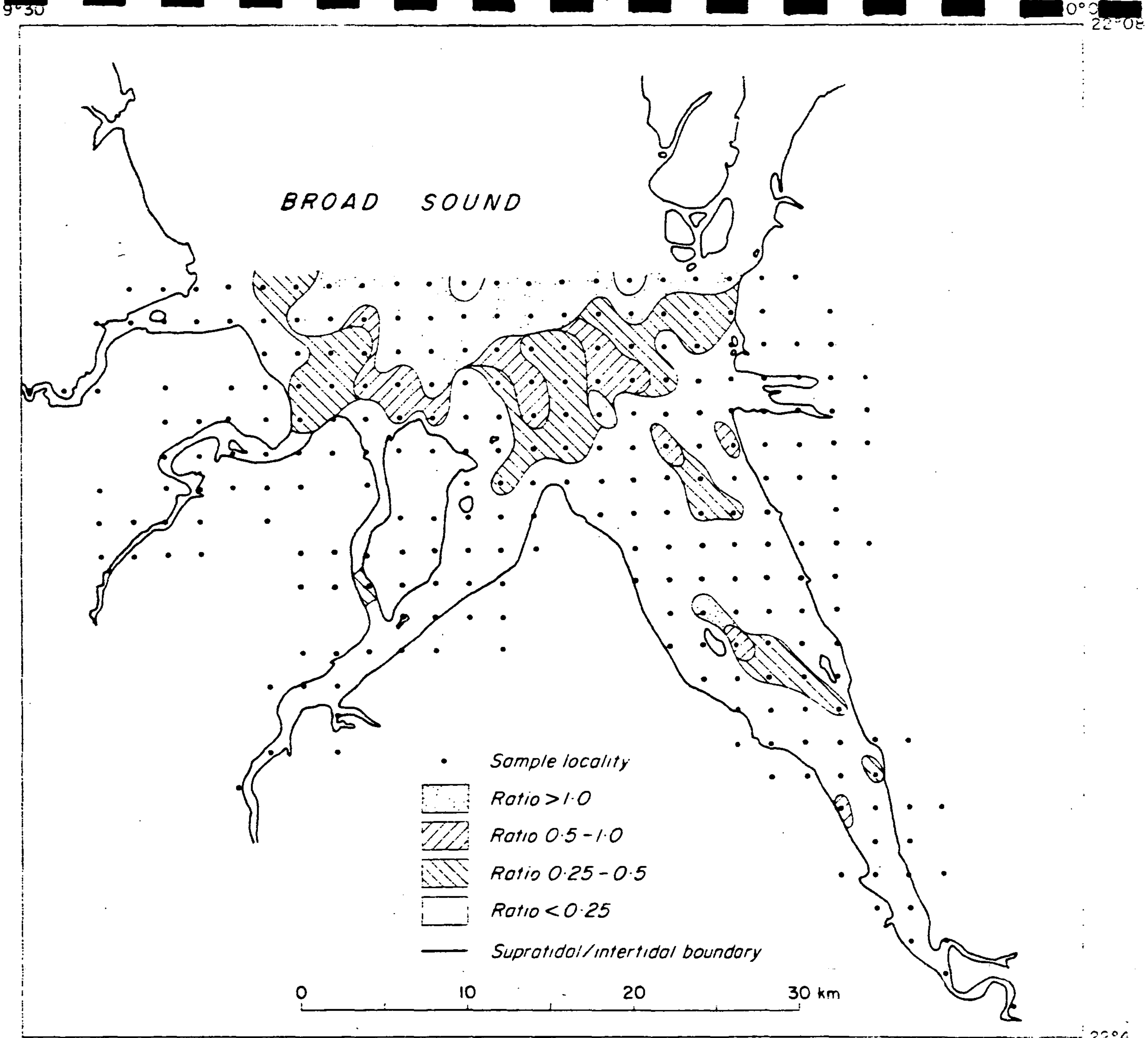

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Fig. 11 Ratio of zircon, tourmaline and rutile to other less stable heavy minerals within the estuary move landward and offshore sediments move landward into the mouth of the estuary.

Therefore, the theoretical arguments based on the relative strength of the ebb and flood tides, the seaward changes in grainsize frequency and ZTR index distributions, and the overall sand-gravel distribution, suggest that the non-carbonate sediments in the estuary consist primarily of terrigenous material derived from the Broad Sound catchments (and are superimposed on relict sediments).

SORTING PROCESS

Given seaward bed-load transportation and the low average river discharge it may seem difficult to explain the enormous amount of recent sedimentation in Broad Sound. Meade (1969, p. 231) gives several examples showing that most river sediment is supplied to estuaries during periods of flood. This is particularly relevant in Broad Sound, as major flooding occurs annually. If most of the terrigenous sediment, which has been shown to be fine sand, silt, and suspended clay, is supplied over a period of a few weeks each year the sorting process indicated is more of a winnowing of the newly deposited fine material during the remainder of the year.

Nevertheless, it is clear that as the bed-load is moved seawards the silt and clay particles are preferentially sorted by the tidal currents. It was indicated earlier that some of this material and previously suspended silt and clay are redeposited in the shallow marine or supratidal zones. These redepositional processes can now be discussed in more detail.

It has already been pointed out that the preferential removal of carbonate silt from the open intertidal environment may indicate that this zone has a higher average energy than the shallow marine environment. This is further supported by the fact that tidal current velocities are greater at the surface than at depth (Cook & Mayo, 1974, in prep.), and the intertidal zone is exposed at low tide whereas the subtidal zone is not. Therefore, the average velocity of the depositing currents must be higher in the intertidal zone than the subtidal zone unless most of the intertidal zone is exposed shortly after the start of ebb tide and before the current velocity builds up. Maximum ebb-tide velocity is reached quite quickly after the change of tide and the intertidal sand banks begin appearing only slightly earlier, so the latter possibility is discounted.

Consequently, silt and clay particles may remain in this relatively low-energy marine environment if they are deposited during slack water. This explains the fiarly high proportion of mud in many of the marine samples containing gravel and coarse sand. Most of the coarse particles are probably relict material from the pre-Holocene land surface, while some have been dumped into this lower-energy zone during Holocene sedimentation. In the high-energy marine channels, the sediments consist only of coarse relict sediments.

Alternatively, the fine suspended particles would rapidly form deposits in areas which were shallow at the top of flood tide, when the flood and ebb currents would be of low energy. Supratidal areas would first form by this process and then rapidly extend. They include the supratidal mudflats and most of the mangrove swamp environment. As the spring tides containing suspended silt and clay particles inundate the supratidal zone the silt particles would be expected to be preferentially deposited in the mangroves since the currents pass through this environment before reaching the mudflats. Also, pools of surface water remain on the mudflats after the spring tides, in contrast to the mangrove environment, where the surface is porous and a gentle seaward slope is usual. As the pools evaporate all the sediment in suspension is deposited and so a greater percentage of clay could be expected in the supratidal flat environment than in the mangrove swamp environment. Both these predictions are supported by the differences between the silt and clay percentages, as well as the carbonate percentages, in the supratidal flat and mangrove swamp environments (Table 1). Flocculation would also be an important mechanism in clay deposition in both environments.

At the present time the growth of the supratidal zone is reaching equilibrium with the energy conditions in the estuary, as can be seen from the erosion of supratidal mangrove deposits at certain positions in the estuary and their redistribution and redeposition.

SEDIMENTATION MODEL

A composite model of the recent sedimentation in Broad Sound can now be formulated. The following sequence of steps outlines this basic model:

1. Maximum sea level was reached about 5-6000 years B.P. (Cook & Polach, 1973). If currents then were as strong as they are today this inundation would winnow out the mud fraction from the soils and stream sediments, leaving any

coarse sand and gravels and pedogenic carbonate nodules as a relict deposit. Therefore, at this time non-carbonate sediment would be supplied from preexisting soils in the present estuary area and from the catchment.

2. Most of the catchment sediment is transported into the estuary during the annual floods. Much of the silt and clay remains in suspension and the remainder (predominantly very fine sand and coarse silt) is initially deposited in the upper reaches of the estuarine portion of the creeks and rivers and at the mouths of the mangrove channels. During the periods between floods, particles finer than 3 phi are removed from the bed-load by the tidal currents. Of the sediment remaining in the bed-load the 2 to 3 phi particles are moved rapidly seawards and tend to form ebb-current oriented sand banks over-lying the relict sediments.

3. The silt and clay winnowed from the incoming sediments, as well as that already suspended, is kept in suspension until the next change of tide and may be redeposited either in the supratidal or the subtidal zones.

4. Apart from some in situ shells in the intertidal and marine zones the biogenic material in the estuary is derived from the marine shelf and intermixed with the locally derived terrigenous material.

An idealized diagram of the suggested sedimentation model is shown in Figure 12. The reason for the two dominant grainsize populations previously noted is now apparent. The two main groupings are broadly the supratidal zone and the subtidal and intertidal zones, and the grain-size populations reflect the genetic differences between the two groups.

From the sedimentation model this two-group system can be more usefully divided into four basic genetic sedimentation units. Throughout the discussion the term 'sorting' will imply that 'a definite physical process has been operative and has effected some separation of particular materials from a larger heterogeneous mass' (Spencer, 1963). The sedimentation units are listed below.

1. The pre-sorting unit, which includes intertidal samples from the upper reaches of the creeks and rivers and the mangrove channel samples. These samples have a significant percentage of grains finer than 3 phi which have not been removed by the tidal currents.

2. The high-energy sorted unit, which corresponds with the high-energy sand facies of the open intertidal and shallow marine environments. Samples from the open intertidal and associated shallow marine samples represent

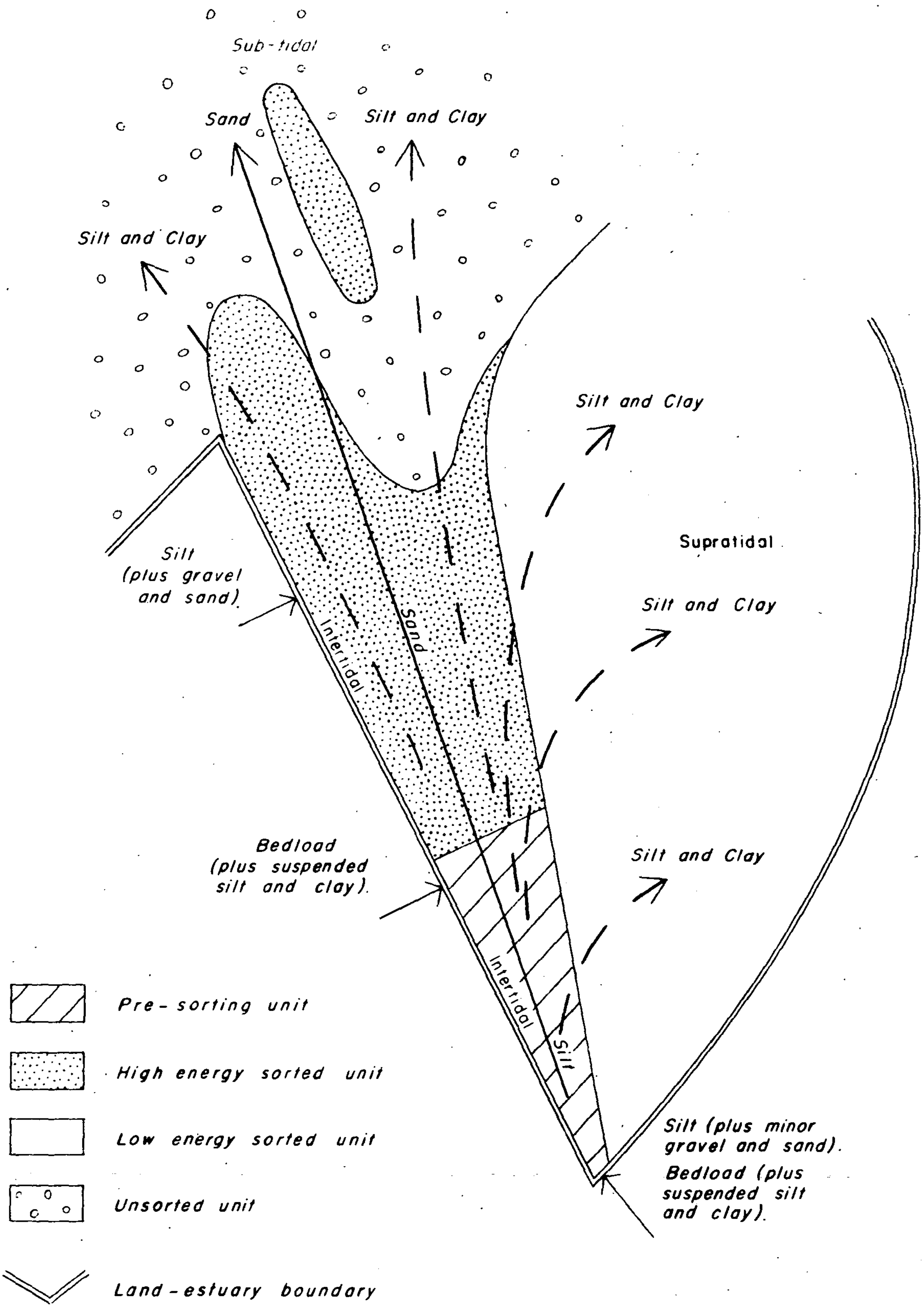

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Fig. 12 Idealized model of the recent non-carbonate sedimentation at Broad Sound.

this unit, which results from the preferential sorting of particles of 2 to 3 phi size under high-energy conditions.

3. The <u>low energy-sorted unit</u>, which is analogous to the supratidal zone and which has been formed by the preferential deposition of silt and clay carried in suspension by the tidal currents. Therefore, in contrast to the previous unit, this unit is a result of low-energy sorting. The unit can be divided into:

(a) the outer supratidal group, with more silt (both carbonate and non-carbonate) and less clay than the next group, and no gravel. Most of the supratidal mangrove samples represent this group.

(b) the remainder of the supratidal zone, in which the sediments characteristically have a very high clay content but also sometimes contain terrigenous gravel. The supratidal flat samples represent this group.

4. The <u>unsorted unit</u>, which consists of shallow marine sediments with a range of particles from clay through to gravel (terrigenous, biogenic, and calcareous nodules), accumulated under relatively low-energy conditions, compared to the sand facies of the open intertidal and shallow marine environments. The sediments include relict and perhaps some recently deposited gravel and coarse sand particles, preferentially sorted 2 to 3 phi sand grains, and previously suspended silt and clay. Some of the silt and clay may also be relict.

<u>Grainsize distribution parameters</u>

The grainsize distribution of terrigenous particles in a sediment sample depends on the original source material and processes of weathering, transportation, deposition, and diagenesis. Many writers have suggested that all sediments are made up of mixtures of three primary lognormal grainsize populations. Folk (1966) notes that 'nature apparently provides us with three dominant modal populations: gravel, sand plus coarse silt, and clay resulting respectively from direct breakage along joint or bedding planes, from granular disintegration and abrasion and from chemical decay'. Spencer (1963) gives definite limits for the median and standard deviation of each of these fundamental populations, and a recent study by Thomas et al. (1972) supports this theory for the sand and clay populations. From the discussions so far it appears that the terrigenous gravel population is insignificant in the Broad Sound area, but the existence of two distinct populations has been mentioned several times. We will return to these two populations after a general discussion of the four grainsize distribution parameters mean, standard deviation, skewness, and kurtosis.

The mean can be imagined as being the point of balance of the grainsize frequency distribution. Given a supply of a full range of grainsizes, the mean would be expected to reflect the energy of the depositing currents whether high or low energy if the sediment is in equilibrium with them. A linear logarithmic relationship between current strength and mean grainsize was found by Allen (1971) in high-energy conditions in the Gironde Estuary. The mean grainsize of sediment from the Broad Sound high-energy sorted unit would also be expected to reflect the prevailing high-energy conditions.

Spencer (1963) suggests that under low-energy conditions the mean would probably not indicate the energy of the environment because sediments dumped in the environment would remain. Although this general rule does apply to the unsorted marine group of Broad Sound samples, the mean grainsize in the low-energy supratidal zone would be expected to reflect this low energy (except in some locations where abundant coarse material is introduced from the land).

Standard deviation is a measure of spread of a frequency distribution and is commonly used as a measure of sorting of sediment samples; as the standard deviation decreases the sorting is said to be improving. A range of terms from 'very well sorted' to 'extremely poorly sorted' has been suggested (Folk, 1965) for samples with standard deviations of less than 0.35 phi units to those with greater than 4.0 phi units. The use of these wrongly associates genetic terms with a normal statistical measure. Every grainsize distribution has a standard deviation value, but whether this value reflects a sorting process depends on the prevailing physical conditions. As was mentioned above the composition of samples from the supratidal zone and the sorted marine and intertidal sands results from low and high energy sorting processes. The absolute standard deviation values of samples in the unsorted marine unit merely indicate the overall spread of grainsizes in the samples, not any particular degree of sorting.

Given the assumption of the three basic grainsize populations and the equation for skewness in Appendix I, the mixing of two or more populations in unequal proportions will result in skewed distributions.

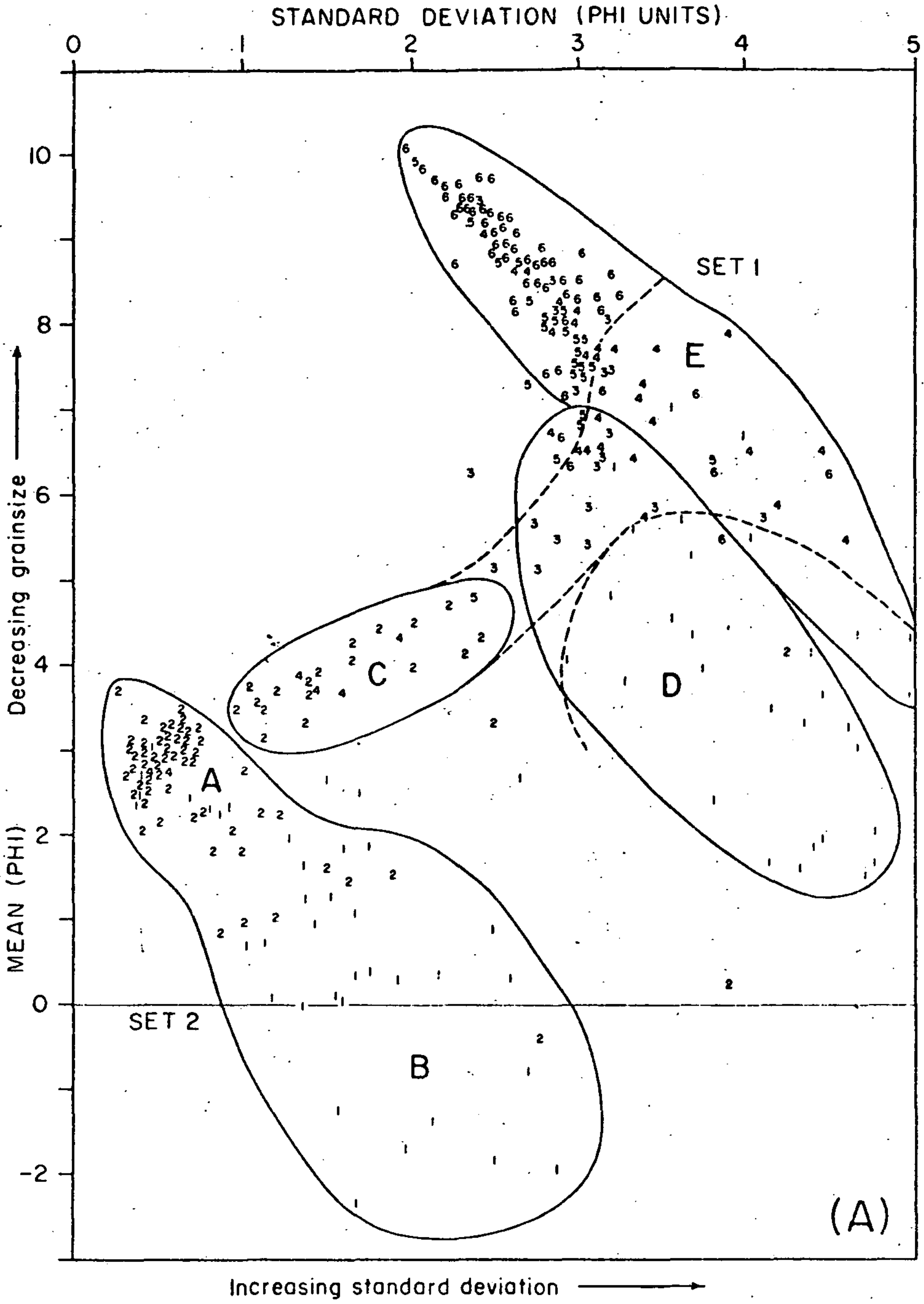
Folk & Ward (1957) discuss the effects of population mixing on the four distribution parameters and argue that they change systematically as the relative proportion of the populations changes. A unimodal distribution, tending to zero skewness, may indicate that the sample was deposited under one set of environmental conditions, but problems arise with numerical interpretations, as the skewness value can be zero for asymmetric distributions. That is, with multi-modal distributions certain positions and sizes of the modes will produce a zero skewness value. Therefore, the interpret skewness values in a study area, the grainsize distributions of individual samples need to be analysed carefully before making final conclusions.

Using the formula for kurtosis in Appendix I, a normal distribution would have a kurtosis of zero. Therefore, kurtosis values will depart from zero with a mixing of the fundamental lognormal populations. The main difference between skewness and kurtosis values is that whereas skewness values are positive if small proportions of a finer grainsize population are mixed with a dominant population and negative if small proportions of a coarser grainsize population are so mixed, kurtosis values are positive in both cases. Negative kurtosis values would result if one of the fundamental lognormally distributed grainsize populations were truncated by some physical process, and the skewness values would be positive or negative, depending on whether the coarse or the fine portion of the distribution was truncated. The mixing of two or more populations in almost equal proportions would also result in negative kurtosis.

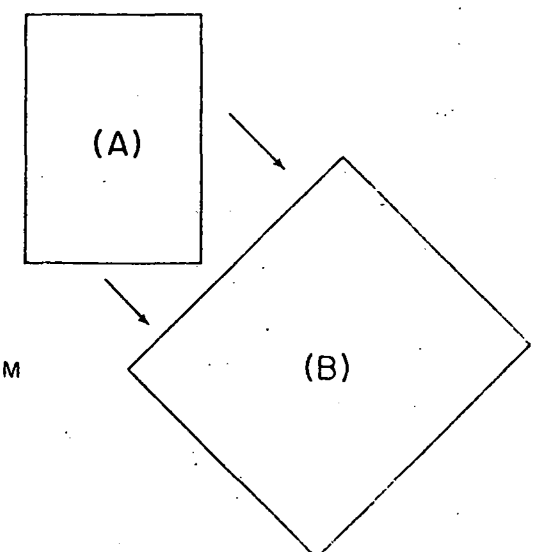
This general outline of the statistical grainsize parameters has only touched on the geological interpretations and associated problems. It is clear at this stage that all available relevant information must be studied before any decisions on the usefulness of these grainsize parameters can be made. For example, two obvious problems relevant to the Broad Sound study are the presence of relict sediments and the occurrence of mud-balls in high energy environments.

SAMPLE CLASSIFICATION

In Figure 13(a), mean grainsize values are plotted against grainsize standard deviations for all samples, each field environment being numbered separately. Skewness can be added by plotting a diagonal line from each sample point on Figure 13(a) and representing the sample as a point along this line, the position depending on the skewness value. The result is shown in Figure 13(b). Because two samples lying on the same diagonal line from Figure 13(a) and having the same skewness would plot onto the same point in Figure 13(b) both figures must be considered when sample groupings are worked out from Figure 13(b). This pseudo-ternary plot reveals five main groupings, A to E, which correspond in both diagrams, except for groups A and



1. Shallow marine
2. } Intertidal
3. }
4. Mangrove channel
5. Mangrove (supratidal)
6. Supratidal mudflat



RELATIONSHIP DIAGRAM

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Fig 13a Plot of mean against standard deviation.

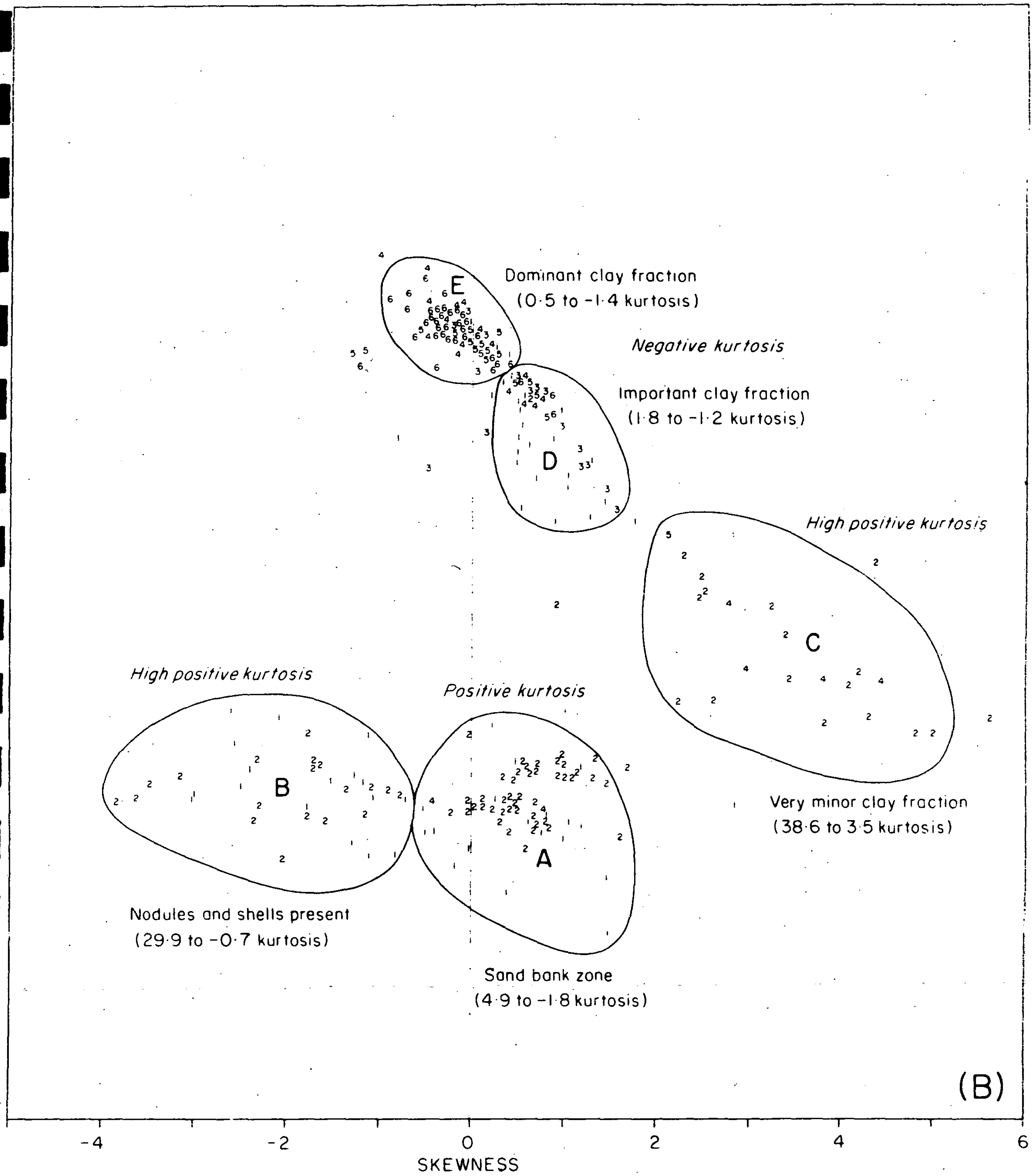

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Fig. 13b Pseudo-ternary mean standard deviation – skewness plot.

B, which overlap to some extent. Finally kurtosis values were added to this plot by indicating the range of kurtosis values and a name describing the dominant kurtosis values in each group. If the groupings can be explained by relating the grainsize parameters to the actual sediment types in each group, all four parameters may be useful interpretative measures for later numerical analysis of the sediments.

The terms suggested by Folk (1965) to classify the parameter values of grainsize distributions are not suitable for the Broad Sound samples because of different methods of determining parameters, the insufficient range of values for the suggested terms, and the problem of using genetic terms, such as well-sorted, to describe standard deviation values. Even the terms suggested for skewness imply a certain shape of the size distribution, such as 'near-symmetrical'; but, as already pointed out, in some circumstances an asymmetric distribution can have a zero skewness value. Later it will be shown that the terms suggested to describe the kurtosis values have similar problems.

Therefore the following descriptive names will be used for the various classes of parameter values on the Broad Sound samples:

Mean	less than 2 phi	coarse
	2 to 4 phi	medium
	4 to 6 phi	fine
	greater than 6 phi	very fine

Standard deviation	0 to 1 phi units,	low
	1 to 2 phi units,	moderate
	2 to 3 phi units,	high
	greater than 3 phi units,	very high

Skewness less than -1	negative
0 to ± 1	zero
+1 to +2	slightly positive
greater than +2	high positive

Kurtosis less than +1	negative
+1 to +5 positive	
greater than +5	high positive.

When describing the sample groupings in Figure 13(b), the terms may not apply to each individual sample in a group, but to the overall tendency of that group.

Samples in group A have a medium mean, low standard deviation zero to slightly positive skewness, and positive kurtosis. Two typical grainsize distributions from this group are shown in Figure 14. These distributions have one dominant mode between 2 and 3 phi, and most of the samples in this group are from the intertidal sand banks and the associated shallow marine sediments. Group A represents the high-energy sorted unit in the sedimentation model. Some samples from the model's pre-sorting group are also included in group A. The low standard deviation reflects the high-energy sorting process previously discussed in detail; the zero skewness with one mode indicates consistent depositional conditions; and the positive kurtosis results from deposition of minor amounts of silt and clay or coarse shell material or both.

High positive kurtosis, high negative skewness, moderate to high standard deviation, and coarse mean characterize group B. Figure 15 clearly shows that the high negative skewness and high positive kurtosis are due to minor modes to the left of the dominant mode. Examination of the samples in this group shows that these minor modes are due to the presence of shells and calcareous nodules. Separating the gravel fraction by sieving (-1 phi cut-off) and analysing the sand and gravel by two different measurement types (actual size by sieving the gravel and hydraulic equivalent size obtained with the settling tube) influence these minor modes. This is shown in Figure 15(b), where the minor coarse mode begins in the first interval of the gravel fraction below the sand-gravel boundary. Had the whole sample been measured using the hydraulic equivalent concept, this mode would probably have occurred to the right of its indicated position or would not have been present as a separate mode at all. Despite this problem the negative skewness in this group may be ascribed to coarse nodules and shells in the samples, as is seen in Figure 15(a), where one minor mode is due to nodules in the sand fraction and the other is due to shells in the gravel fraction. Again the samples in this group are from the high-energy sand banks of the subtidal and intertidal zones.

The sedimentation model only considered non-calcareous particles in detail, and the grainsize analysis of the total sediment has separated group B from group A because of the calcareous nodule and shell content. Groups A and B then both represent the sedimentation model's high-energy sorted unit but can be separated on the coarse

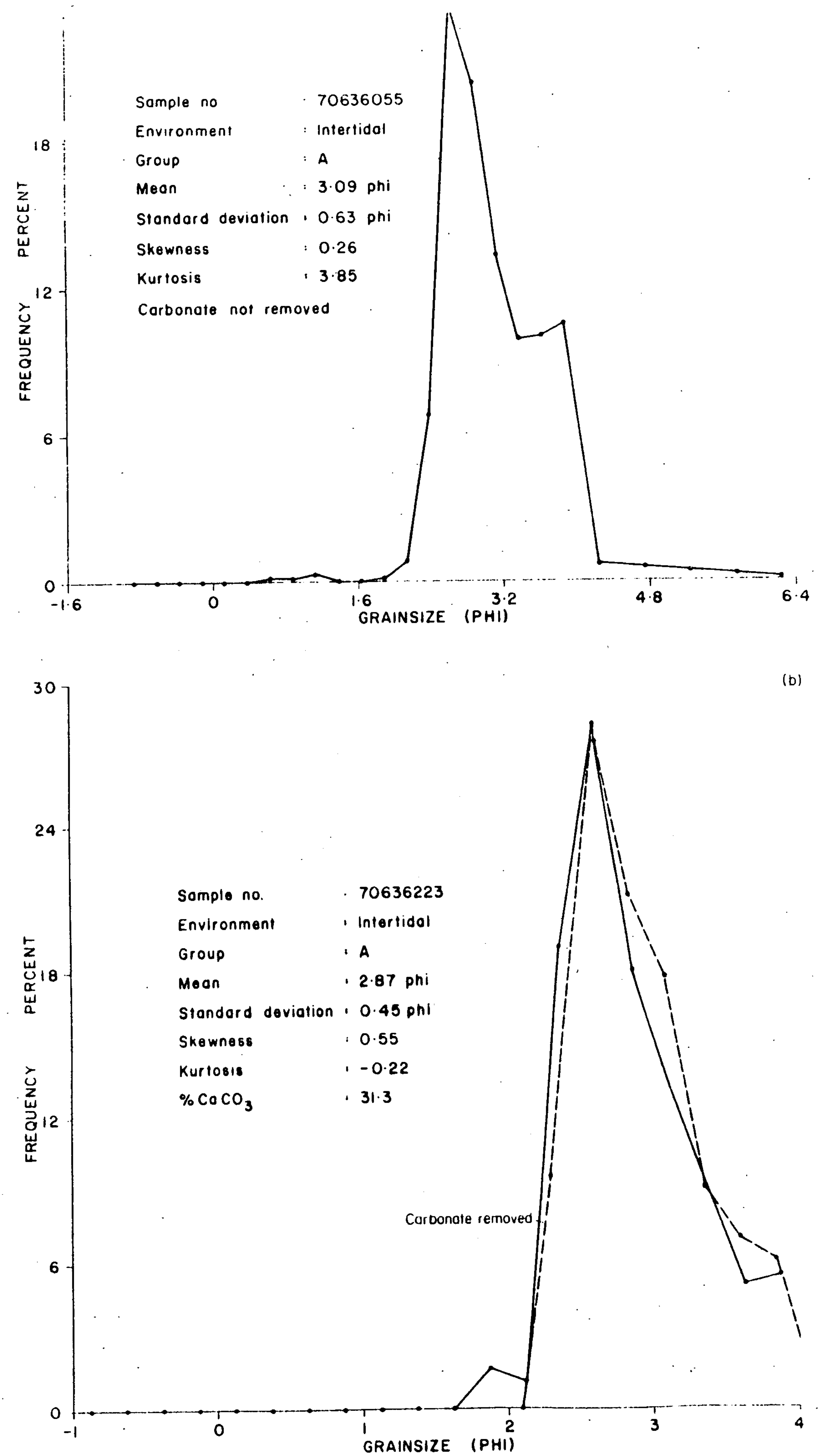

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Fig. 14 Typical grainsize distribution for Group A.

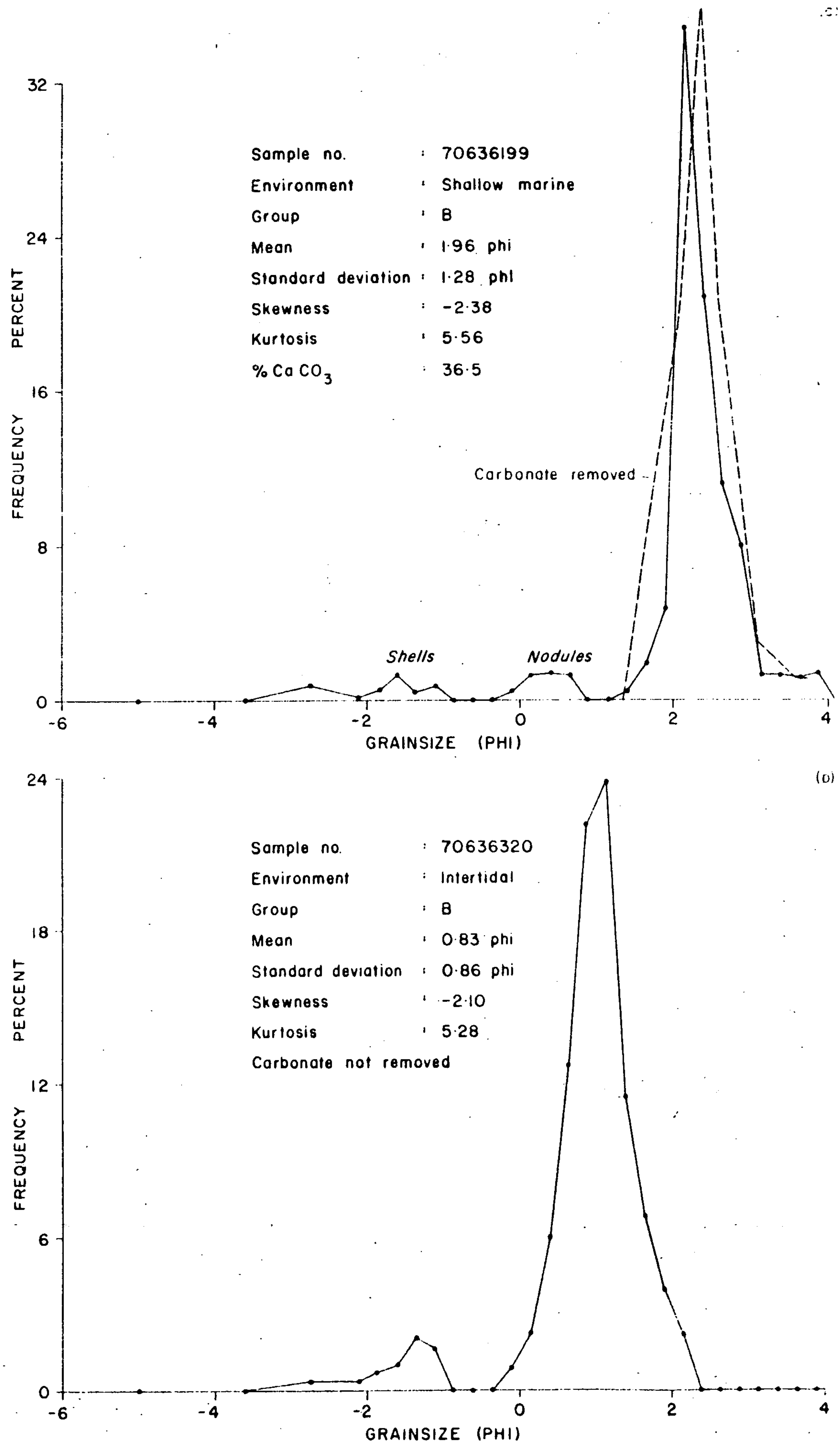

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Fig. 15 Typical grainsize distribution for Group B.

carbonate content. Figure 13 shows clearly the increasing mean, standard deviation, and kurtosis, and decreasing skewness, from groups A to B.

The samples in group C have high positive kurtosis, high positive skewness, medium mean, and moderate standard deviation. The frequency distributions in this group might be expected to extend out to the right of the mean owing to the presence of grains finer than the mean grainsize. Figure 10 shows a typical example in this group, but the distribution appears negatively skewed (similar to group B) and only a small amount (2.8 percent of the total) of fine particles makes up the right 'tail'. This was due to extrapolation of the clay weight remaining, after the pipette analysis was completed down to 9 phi. The sum of the percent frequencies of the 5 extrapolated intervals does not appear to add to 2.8 on Figure 16, but they have been scaled for true diagrammatic representation of the distribution (Mayo, 1972). In fact this 2.8 percent of the sample changes the skewness from 0.29 to 3.86. As such a small proportion of the sample can change the skewness so drastically, interpretations made from skewness values of the Broad Sound samples are unlikely to be reliable: this can also be deduced from Figure 17, which shows a typical negatively skewed frequency distribution of group B, the minor coase modes being due to shells and nodules. Because of a little clay (0.96 percent) far removed from the mean size, the resulting skewness value is 0.51, placing the sample in group A. (Problems whose answers change drastically with a small change in the input data are called ill-conditioned - a common difficulty in numerical analysis (Dorn & McCracken, 1972). This problem will be discussed in more detail later in relation to the grainsize parameters of the Broad Sound sediments.

Almost all the samples in group C correspond to the sedimentation model's pre-sorting unit, so that despite the ill-conditioning problem this genetic group is separated by the grainsize measures. It is important to note, though, that group C was separated in Figure 13(a) before the skewness values were plotted.

Groups D and E have medium to fine means and they are characterized by high to very high standard deviation, zero to slightly positive skewness, and negative kurtosis. Unlike group A, a skewness value close to zero does not coincide with a unimodal distribution. All the samples in group D, which are mostly from the open intertidal, shallow marine, and mangrove channel environments, have a secondary mode in the clay fraction (Fig. 18), which explains the positive skewness of the group. The open intertidal and mangrove channel samples in group D correspond to the

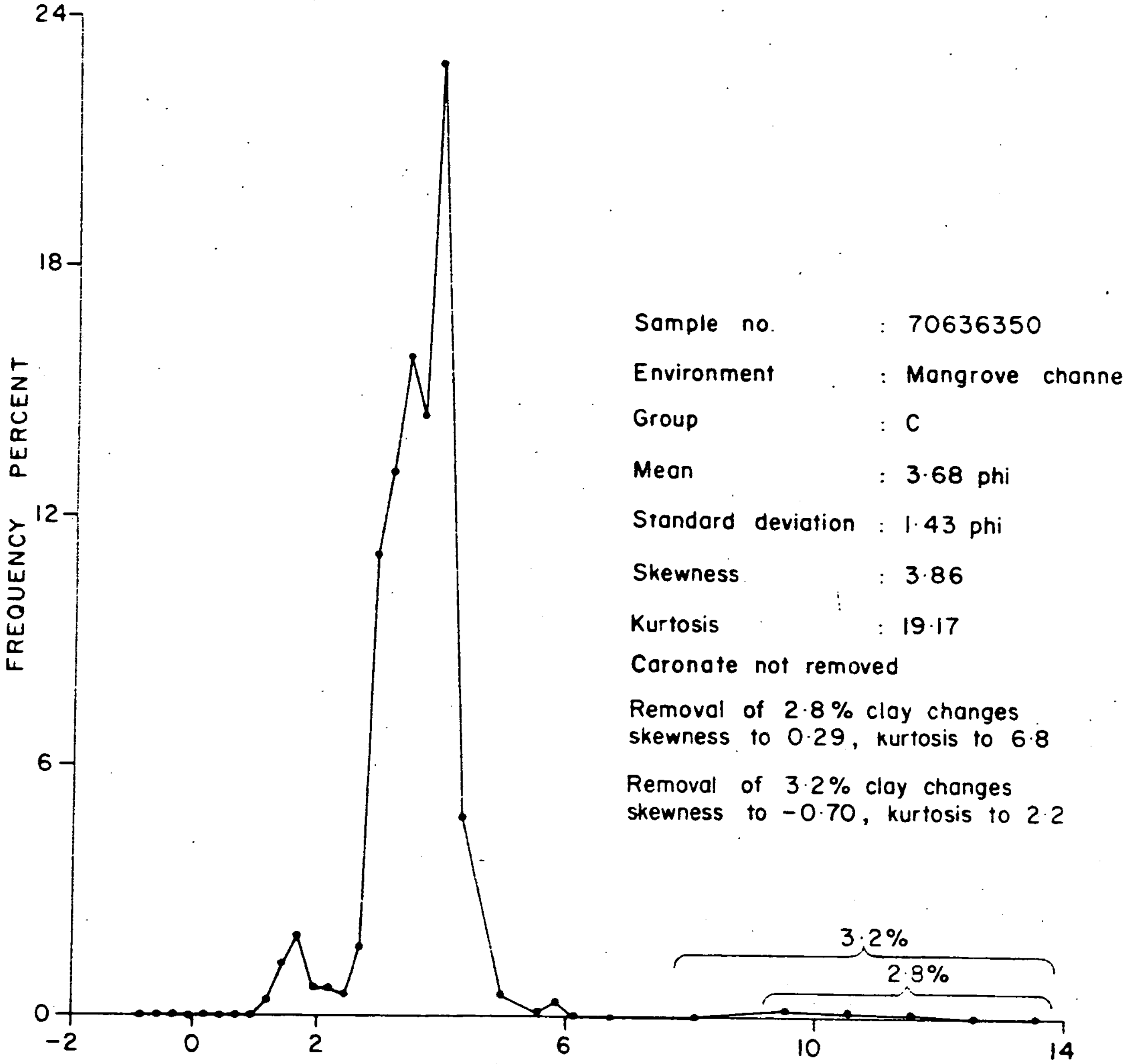

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Fig. 16 Typical grainsize distribution for Group C

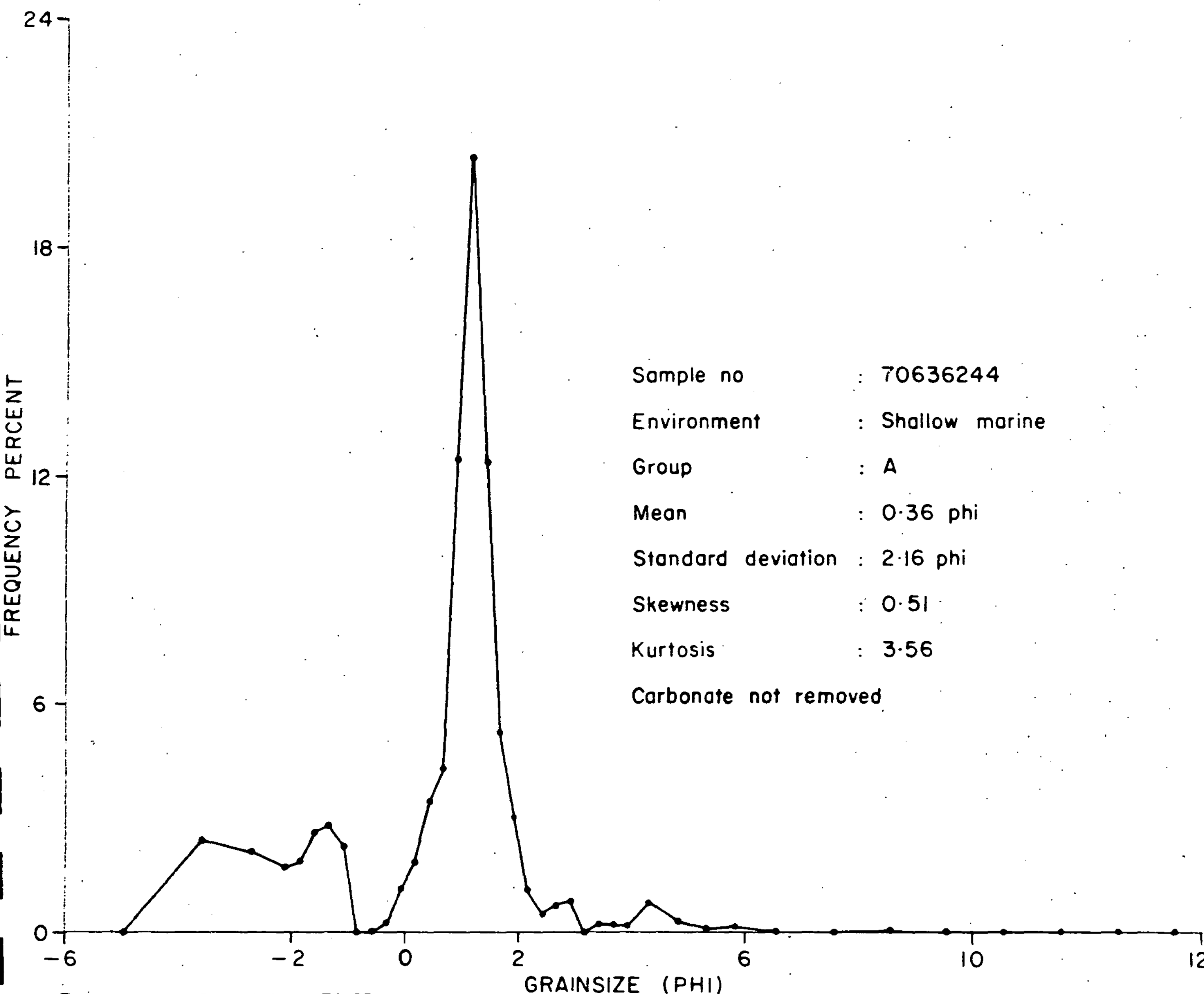

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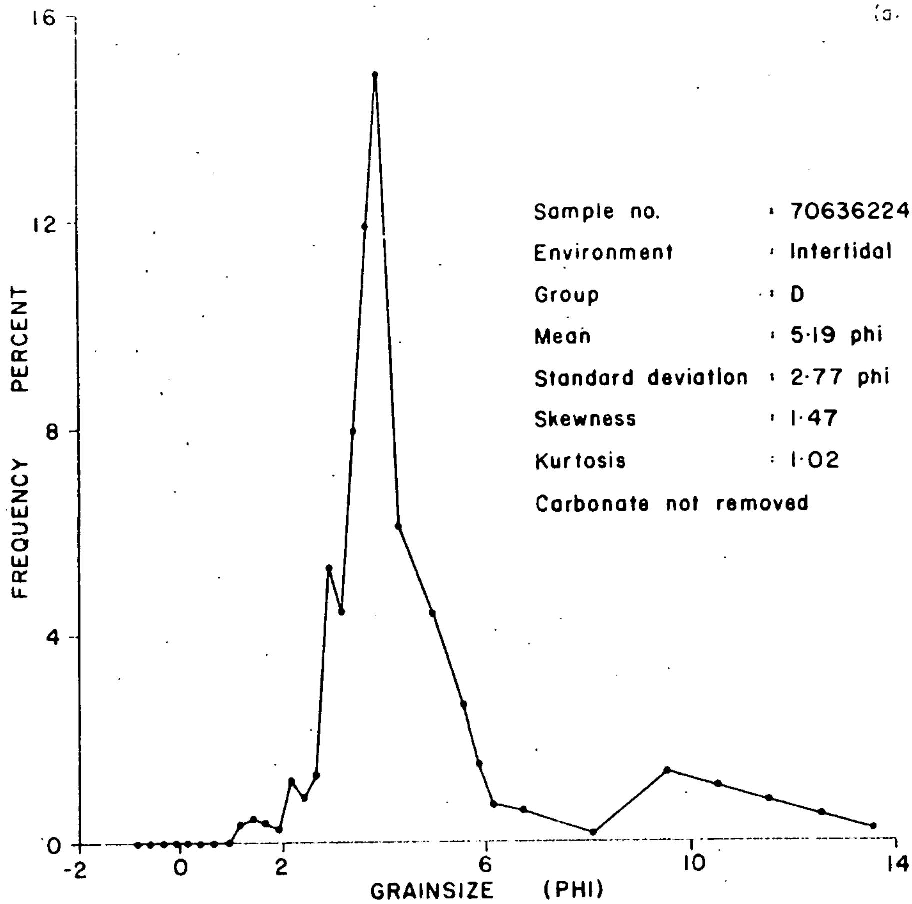
Fig. 17 Typical grainsize distribution for Group A



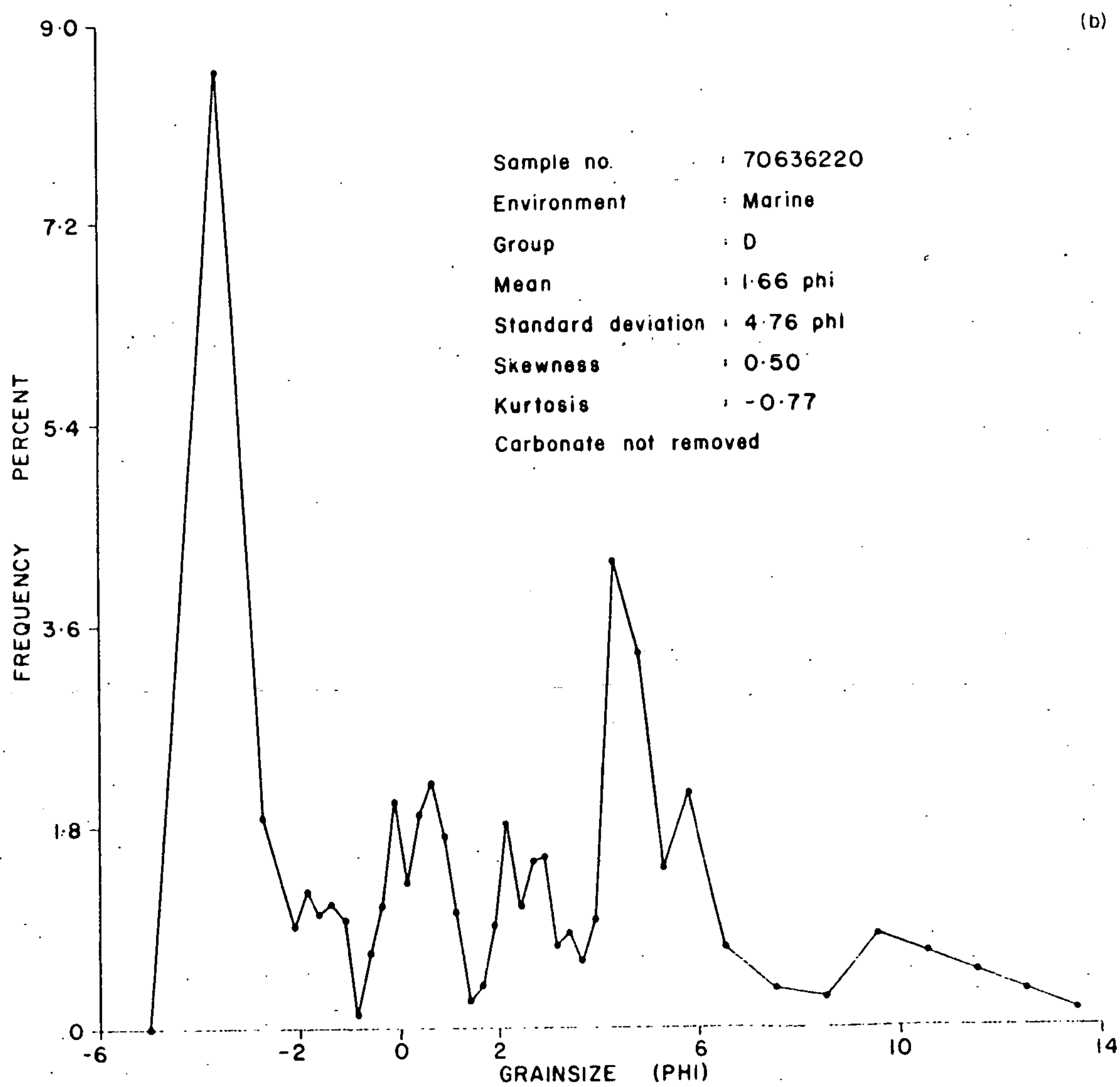


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Fig 18 Typical grainsize distribution for Group D.

presorting unit from the model, and the shallow marine samples (Fig. 18(b)) represent the unsorted unit. As was discussed previously the clay fraction has been redeposited - although some may be relict - in these marine samples, but the tidal currents have not sorted it out from the mangrove channel and open intertidal samples. The clay fraction in some samples in the group may also be due to minor processes such as the formation of mud balls in the high-energy (sand-bank) environment. It is also important to note that although the clay fraction in group C is much smaller than in group D, its effect on the kurtosis of the group C samples far outweighs that of the group D samples because of the greater distance of this mode from the mean grainsize value.

Most samples in group E, most of which are from the supratidal flat and supratidal mangrove environments, have a bimodal grainsize distribution (Fig. 19), with one mode in the clay fraction greater than 8 phi and the other between 5 and 6 phi. This results in low kurtosis and skewness values. With some samples, significant modes also occur in the sand fraction owing to the washing in of particles from the nearby catchment. The clay fraction mode probably represents clay which is deposited as the pools remaining after each spring tide evaporate, or reflects clay particles originally deposited as floccules which were perhaps hydraulically equivalent to the silt-sized particles. The 5-6 phi mode reflects the supply of particles from the estuary (and a little from nearby land), and the velocity of currents inundating the mudflats during spring tides. In contrast, the finest modes in the samples found in the upper reaches of the creeks and rivers entering Broad Sound were between 4 and 5 phi. Therefore, given the postulated sedimentation model most of the particles deposited in the supratidal zone enter the estuary in suspension. That is, although the coarse silt is being winnowed from the sediments entering the estuary and deposited in the supratidal zone, the deposition in this zone is dominated by the medium to very fine silt plus clay material from the catchment which entered the estuary in suspension. Samples in Group E accord with the low-energy sorted unit in the depositional model, except for the shallow marine and mangrove channel samples which accord with the unsorted and the pre-sorting units respectively.

To summarize the geological conclusions from the groupings in Figure 13(b): groups A and B represent the high-energy sorted unit, group B being separated from A by its coarse carbonate shell and nodule content; groups C, D, and E reflect increasing abundance of clay. The intertidal and mangrove channel samples from groups C, D, and E represent the pre-sorting unit, the marine samples in groups

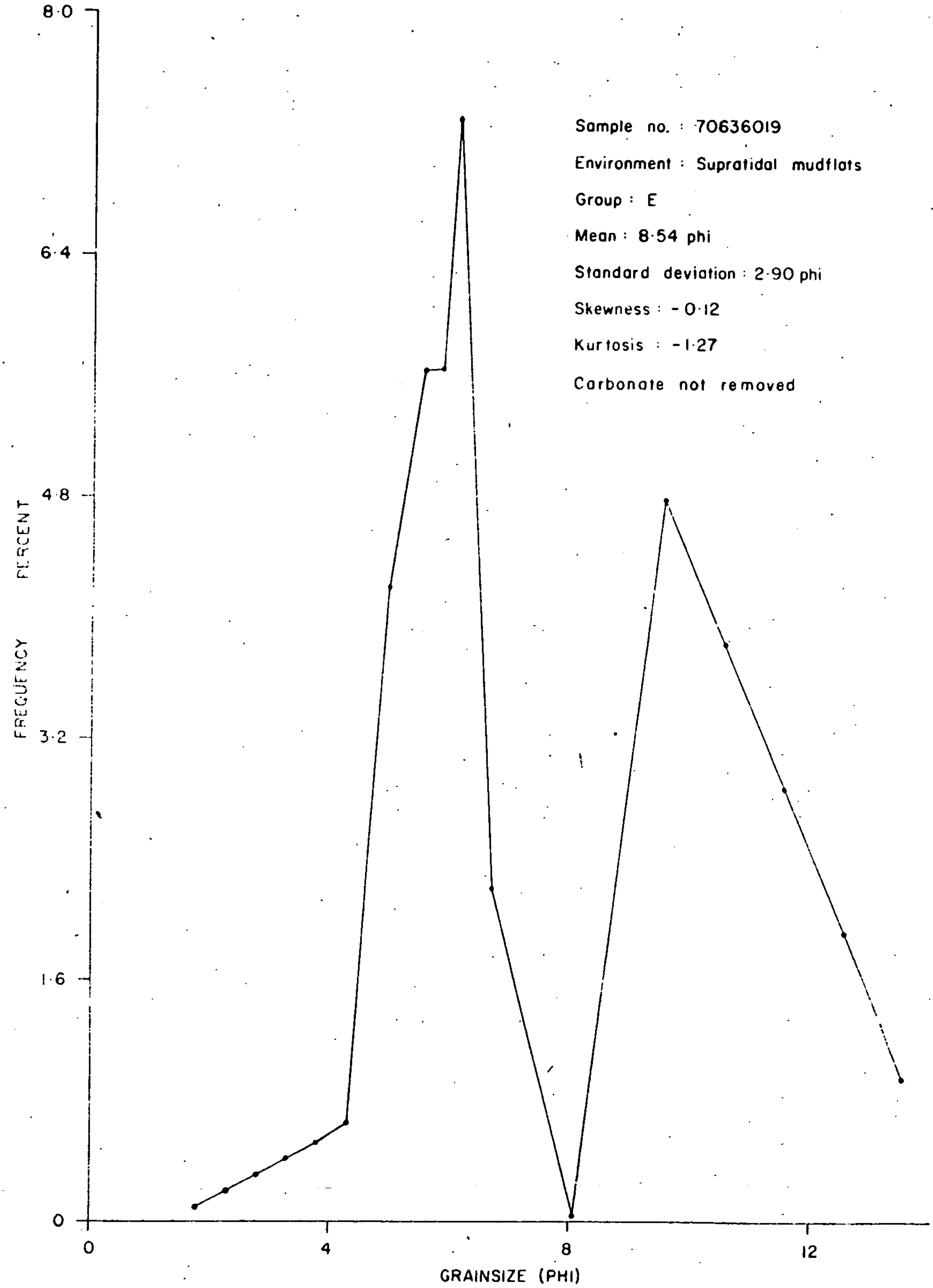

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Fig. 19 Typical grainsize distributions for Group E.

D and E are from the unsorted unit, and the supratidal mangrove and mudflat samples in group D represent the low-energy sorted unit. The extension of the pre-sorting unit from Group C through to group E seems reasonable as the grainsize distributions would change markedly as the silt and clay are winnowed from the samples.

Therefore, the five groups in Figure 13(b) can be interpreted geologically; but the geological groups (the sedimentation model's units) overlap the physical groupings to some extent. The overlap points to the possibility that Figure 13(a) may separate the geological groupings, because, skewness values are avoid. Before this possibility is explored the ill-conditioning problem (small changes in data producing large changes in the answers) with the grainsize parameters must be studied in detail.

ILL-CONDITIONING PROBLEM

The high kurtosis values in groups B and C generally reflect minor modes of gravel and mud separated from the major grainsize mode. To get an idea of the effect of this ill-conditioning, the gravel results from a selection of the group B samples, and the clay readings (9 phi to 14 phi) in the group C samples, were left out and the values of the four grainsize distribution parameters were re-determined. The percentage change in the value of each of the four parameters was calculated as

$$\frac{(\text{original value} - \text{new value}) \times 100}{\text{original value}}$$

It was necessary to divide by the original value and not the new value as the skewness and kurtosis values of the samples with the minor modes removed were often very close to zero, which resulted in percentage changes up to 11000 percent. The percent change was divided by the percent removed from the original sample to give an estimate of the percent change in the parameter due to removal of one percent of either the coarse or fine minor mode. The results of these calculations are given in Table 3.

From this table one can see that the percent changes in the mean grainsize measure are of the same order as the one percent change in the data. That is, the determination of this parameter is quite well-conditioned. The standard deviation shows large percentage changes, mostly between about 10 and 30, resulting from a one percent change in the data. The importance of the size of the

Table 3 - Percentage changes in the grainsize distribution parameter values given the removal at 1% of the coarse (group B) or fine (group C) extremity of the distribution

GROUP C

Sample	% of last 5 class intervals	Mean (% Increase)	Standard deviation (% Decrease)	Skewness (% Decrease)	Kurtosis (% Decrease)
4	6.6	1.6	10.9	10.2	10.1
10	3.6	1.8	17.2	16.1	20.7
15	7.6	1.5	7.5	9.9	3.3
20	2.9	2.0	18.9	32.7	27.2
21	4.4	1.8	12.2	22.1	16.9
26	1.0	2.2	37.6	77.7	79.1
31	1.4	2.1	41.4	35.6	55.6
40	1.8	1.9	31.2	36.6	48.0
48	1.5	4.5	29.9	71.0	50.3
81	11.0	2.1	23.3	11.6	-5.6
83	9.7	2.1	22.8	-2.8	-7.2
109	10.0	1.4	6.3	4.5	-1.8
111	4.9	1.6	11.9	7.1	7.1
252	11.9	1.4	17.4	0.1	-10.5
260	2.6	1.9	16.1	27.6	15.1
283	1.5	2.5	30.3	68.4	57.9
347	3.0	1.9	19.8	30.2	18.0
348	7.1	1.6	8.9	11.9	5.1
349	3.4	2.0	13.1	32.9	21.5
350	2.8	2.0	17.9	33.1	23.0

GROUP B

Sample	% of last 5 class intervals	Mean (% Increase)	Standard deviation (% Decrease)	Skewness (% Decrease)	Kurtosis (% Decrease)
61	2.7	1.9	14.8	37.4	34.0
73	1.7	1.7	11.9	22.8	39.6
87	1.6	1.8	28.2	62.8	61.1
88	8.0	2.9	7.5	8.5	4.3
91	2.4	1.9	12.7	31.8	35.2
96	2.0	1.9	17.0	43.7	45.8
99	4.2	1.2	13.3	13.9	19.8
145	3.2	2.2	15.9	34.0	29.9
187	4.1	2.2	12.7	27.0	23.8
188	1.6	1.9	24.3	69.7	49.4
199	7.0	2.2	7.3	21.4	3.1
201	9.2	2.2	7.9	11.9	12.9
305	3.9	2.2	5.8	22.0	21.7
320	7.7	3.3	6.4	14.1	12.7

changes is apparent when the precision of the grainsize techniques is remembered, for 5 percent change in the data would result in about 100 percent change in the standard deviation value. Of course, the examples shown are extreme cases, with data completely removed from one end of the grainsize range, but often this is precisely the case when a percent mud cut-off is used to decide whether or not to pipette the mud fraction. Ideally, a change in any measured parameter should reflect a change of the same order of magnitude intthe input data. The mean grainsize measure seems to satisfy this, even in the extreme case above, but the standard deviaiton over-reacts to changes in the input data.

It is interesting to speculate on the usefulness of the median as a grainsize measure on these results presented for the mean grainsize values. The median by definition is less affected by changes in the extremes of a grainsize distribution than the mean, but if the determination of the mean is well-conditioned, even in the above extreme case perhaps the median as a grainsize measure will not satisfactorily reflect changes in the input data. This view is supported by Folk (1965).

Most of the changes in skewness values range between 10 and 70 percent, the worst sample having 78 percent change. Therefore, a 5 percent change in the data from the distribution extremities can change the skewness value by as much as 400 percent.

The percentage changes in the kurtosis values can be as high as the skewness changes, but the complicate the problem the kurtosis value can actually increase in some cases when data are removed from the extremities of the grainsize distribution. This is shown in the group C results in Table 2 by the negative percentage change in the kurtosis in some samples. These samples also had less than 10 percent changes in the skewness value and had higher percentage clay content in the 9 Ø to 14 Ø range than the other samples in this group. This phenomenon is difficult to explain, but it is obviously related to the amount of clay removed from the calculation and the consequent increase in the frequency percent of the remaining grainsize classes, especially those at the opposite extreme of the distribution. Therefore, not only is the determination of kurtosis values poorly conditioned but the resulting changes in the parameters for similar data changes vary in direction.

The changes in the skewness and kurtosis values in these samples are considered too high to enable reliable interpretations from these parameters, when the precision of the grainsize techniques is taken into account. At first it might seem reasonable simply to remove groups B and C from any future analysis of the results, but of course the problem is not just limited to samples in those groups. This was illustrated previously with Figure 17. Therefore it is concluded that with the Broad Sound samples the skewness and kurtosis determinations are far too sensitive to enable worthwhile interpretations to be made.

Even though the standard deviation determinations are also very sensitive to changes in the input data they are not as ill-conditioned as the skewness and kurtosis determinations, and the size and direction of the changes can be predicted with some confidence. Therefore, only the two parameters mean grainsize and standard deviation are used to attempt definitive geological interpretations, although some X-Y plots including skewness and kurtosis are given later to enable some comparison with other studies. The ill-conditioning problem also shows the difficulty of verbally classifying the skewness and kurtosis values with names which imply the shape of the frequency distribution. Small changes in the data shown above can make drastic changes in the skewness and kurtosis values, but the overall shape of the distribution does not change significantly. That is, the descriptive term may not correspond with the actual shape of the curve. For example, using Folk's (1965) descriptive terms for skewness the sample shown in Figure 17 would be 'strongly fine-skewed', but the actual distribution appears to be skewed with the presence of coarse modes. A simple scheme for describing ranges of parameter values which does not incorporate genetic implications nor infer the shape of the grainsize distribution should be used.

GEOLOGICAL INTERPRETATIONS

Returning to Figure 13 (a & b), a further reason for not using skewness values for interpretations is apparent. Samples from groups D and E are quite distinct and spread out in Figure 13 (a), but the skewness values of most samples in these groups lie between plus and minus one. Further, the samples in group A have much the same range of skewness values as groups D and E. Group A represents samples with unimodal distributions from the high energy sand banks of the intertidal and subtidal zones, and groups D and E represent samples with bimodal distributions from the pre-sorted unit, the low-energy sorted unit, and the shallow-marine unsorted unit. None of these various modes of formation nor of the differing distributions are distinguished by the skewness values. In fact, only the samples with ill-conditioning problems are distinguished.

Similar criticisms can be applied to the kurtosis values. This leaves the plot of mean grainsize against standard deviated to be interpreted geologically.

Figure 20 shows the same plot as Figure 13(a) except that the axes have been reversed. The bulk of the samples appear to follow a sinusoidal trend similar to that found by Thomas et al. (1972) with two basic end-member populations of clay and sand. Folk (1957) also noted this type of trend with gravel and sand end-member populations and predicted a continuation of this sinusoidal trend into the clay population as a result of the mixing of various proportions of the two end-members. With the Broad Sound samples, both the sedimentation model as well as the ill-conditioning problem must be considered to explain fully the mean/standard deviation plot.

Using the previous discussions on the links between the groups in Figure 13 together with the sedimentation model, Figure 20 can be partitioned into an unsorted unit, a pre-sorting unit, and sorted low and high energy units. The same partitioning is shown in Figure 13(a). Remembering that the means and standard deviations were determined on the total sediment, including $CaCO_3$ particles, it is clear that the proposition of two basic grainsize populations is supported. The two populations are indicated on Figure 20 by the high concentration of samples in two separate zones. An important difference between the silt-clay population and that of other studies is that the Broad Sound population includes sediments with a bimodal grainsize distribution. Furthermore, not all the samples follow the theoretical sinusoidal trend, and this suggests that not all the Broad Sound samples are related to these two basic populations.

The studies by Thomas et al. (1972) and Spencer (1963) suggest expected mean and standard deviation ranges for the sand and clay basic populations; mean from 1.5 to 4.0 phi and standard deviation from 0.3 to 1.5 phi units for the sand population, and mean from 7.0 to 9.5 phi and standard deviation from 1.5 to 3.0 phi units for the clay population. The fundamental non-calcareous sand population in this study is shown in the lower right portion of the sorted high-energy unit on Figure 20, the extension of the plot upwards and to the left of the basic population being due to the presence of in situ shells in some of the high-energy sand bank samples. The means of samples in this population range from 2.0 phi to 3.5 phi and the standard deviations from 0.3 to 0.8 phi units; the means are representative of the modal size in the sediments as the grainsize distribution is unimodal with low standard deviations, but the suggestion discussed earlier that the

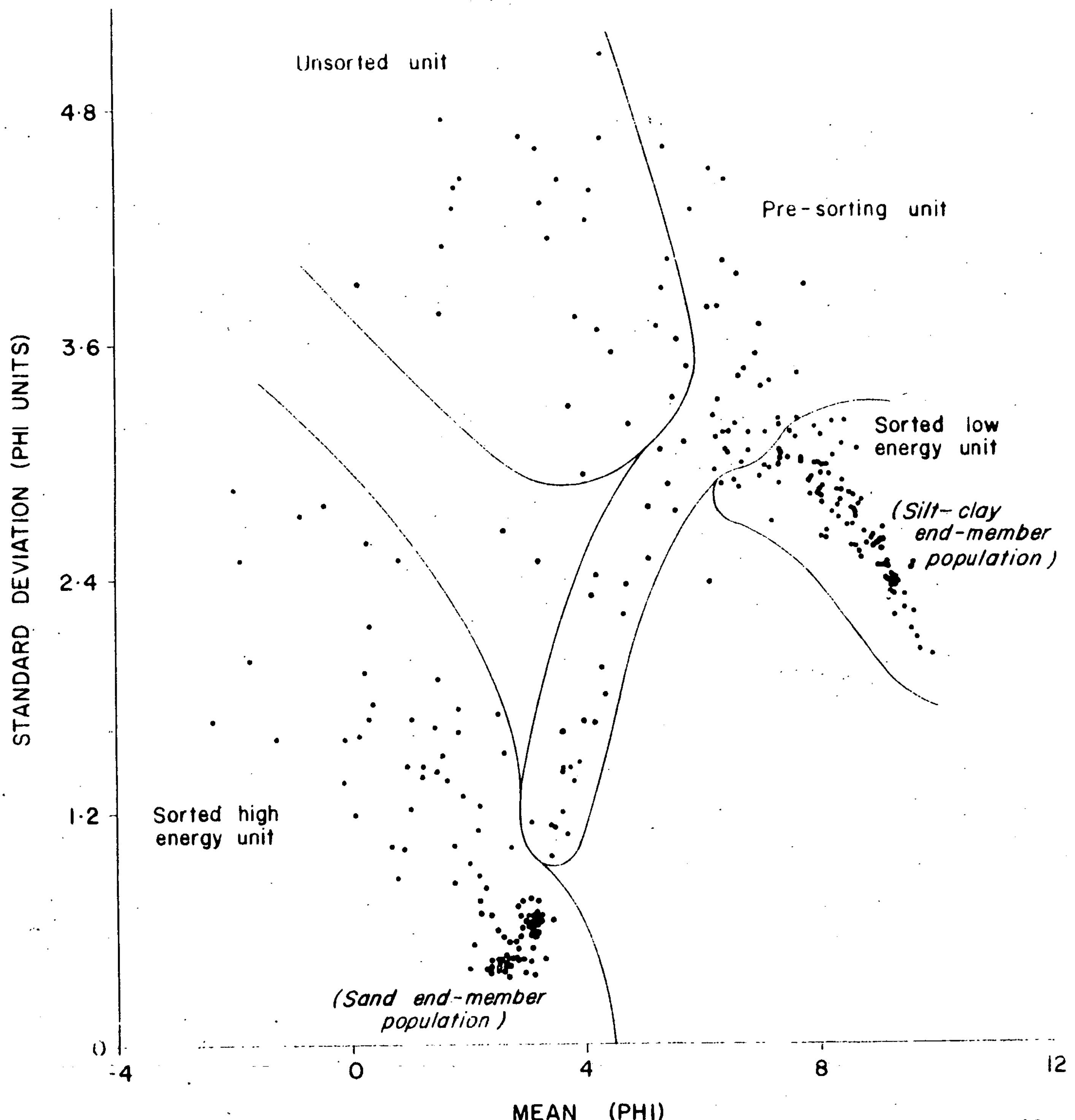

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Fig. 20 Mean standard deviation plot.

basic sand population is due to the abundant supply of particles resulting from granular disintegration and abrasion needs some qualificiation. It has been shown that there is no dominant sand mode in the sediments entering Broad Sound, and the basic sand population in the estuary sediments results primarily from the sorting action of the tidal currents. The sand-size particles may have been formed by disintegration and abrasion, but certainly did not constitute a dominant sediment supply mode.

The silt-clay basic population is represented by the low carbonate supratidal (mangrove swamp and mudflat) samples of the sorted low-energy unit. The means of the samples in this population range from 7.0 to 10.0 phi and the standard deviations from 2.0 to 3.5 phi units. In the Broad Sound estuary, silt and clay particles are dominant in the sediment supply, but it is impossible to determine whether there is only one dominant supply mode in the silt/clay range as the coarse silt enters the estuary as bed load, whereas the medium to fine silt and clay is suspended. Certainly the grainsize distributions of samples representing this population are bimodal with high standard deviation, and therefore the mean does not represent the mode. The resulting silt-clay population is due not only to the abundant supply of these particles, but also to the low-energy sorting processes discussed earlier. Therefore, although this concept of end-member grainsize populations is a very useful interpretative tool, the range in mean value may not indicate the true modal sizes of the sediments in that population, and all the process of sedimentation must be considered when determining the reasons for the existence of the populations in each particular study area.

Plots of the samples from the pre-sorting unit link the two end-member populations and complete the sinusoidal trend. The silt and clay particles removed from the pre-sorting unit form the basic silt-clay population and the remaining sorted sands form the sand end-member population, so the sinusoidal trend is not the result of a simple intermixing of the two populations. Further, the group C samples in Figure 13 are those that form the main elongated link between the two populations and these samples with only minor clay content are those that were shown to produce the ill-conditioned determinations of the standard deviation values. Removal of the small amounts of clay in these samples results in their plotting with the sand end-member population and so cutting out the simusoidal trend. Despite this, the linking of the two groups is geologically meaningful and as the direction of the changes in the standard deviation with changing amounts of clay is predictable (but over-sensitive), it should help with later geological interpretations.

The samples representing the unsorted unit characteristically have a significant mode in the clay size range, but at the same time contain coarse shell and nodule particles with varying amounts of sand and silt. Therefore, these samples plot away from the other units containing high mud values, in the same way as the samples containing coarse shells and nodules in the sorted high-energy unit extend upwards to the left from the sand end-member population.

The two grainsize parameters, mean and standard deviation, seem to distinguish successfully four main sedimentation groupings. The geological interpretations from changes in the mean and standard deviation values are different in each unit. Within the pre-sorting unit, decreasing standard deviation with decreasing mean grainsize (increasing size) corresponds to a decrease in mud content as this fraction is removed by the tidal currents. Increasing standard deviation with decreasing mean in the sorted high energy unit indicates increasing amounts of in situ shells and calcareous nodules within the sorted sands, which also represents a move from the intertidal to the sub-tidal sections of the unit. The same combination of increasing standard deviation with decreasing mean in the sorted low-energy unit represents the transition from sediments of the supratidal flats to sediments with a higher sand and silt content. This combination with increasing carbonate content points to a movement to the supratidal zone of the mangrove swamp environment; or to sediments containing significant sand and silt washed from the land. As expected with the unsorted unit there is no clear trend with the two variables, but there is a suggestion of increasing standard deviation and decreasing mean as the proportion of shells, nodules, and terrigenous gravel increases.

These interpretations should be most important when interrelations between samples and variables are being determined later. Given the sedimentation unit, changes in the mean and standard deviation values can therefore be used to interpret the changes in other measured variables. Certainly, this fact gives strong argument to classifying the Broad Sound samples into these separate genetic units before carrying out any detailed numerical analysis on each group.

The separate units show clearly the problems of general interpretations from the mean grainsize values. Only with the two end-member populations do the mean grainsize values reflect the average velocity of deposition. The decrease in mean grainsize values for the rest of the sorted high-energy unit is due to the presence of shells and nodules, the sizes of which are not always related to the current velocity. Similarly, the amount of mud remaining at any location in the pre-sorting unit is unrelated to the average current velocity, and the relatively low current velocities in the unsorted unit bear little relation to the grainsize of the sediments. Similarly the fact that samples from the unsorted unit, the pre-sorting unit, and the sorted low energy unit can all have similar standard deviation values points to a comparable interpretative problem. Absolute standard deviation values are not in general a measure of the degree of sorting in the genetic sense, nor of the range of velocity of the depositing currents. Even the different average standard deviation of the two end-member sorted populations has limited significance. Alternatively, within the genetic units, changes in the standard deviation values may indicate different levels of physical sorting. This is so in the sorted high-energy unit, the sorted low-energy unit, and the pre-sorting unit.

In conclusion, although absolute mean and standard deviation values of the Broad Sound samples alone are not useful for geological interpretations, the combination of the two parameters successfully classifies the samples into separate genetic groups. Within each of these units the changes in both the mean and standard deviation values can be interpreted geologically.

ERROR ANALYSIS

Before a final decision can be made as to whether the mean and standard deviation of grainsize distributions may be used in future numerical analyses, it is necessary to test the significance of the combined analytical and sampling error of both these variables. This was done using one-way analysis of variance on a set of samples from the outer-supratidal zone in the low-energy sorted unit (mangrove swamp samples), the supratidal flat environment in the low-energy sorted unit, and the pre-sorting unit (open intertidal and mangrove channel samples). Triplicate samples were taken at seven randomly selected localities in both the mangrove and mudflat environments and eight in the pre-sorting unit. The results are shown in Table 4.

As was explained earlier, one-way analysis of variance tests for differences between the means of each set of triplicate samples in the above units. If there is no significant difference between the sets for a particular variable, then the combination of errors may mask any variation. The F distribution is used to test for

TABLE 4

Tests for significance of combined analytical and sampling error. (F(6, 14) at 95% = 2.85)
(F(7, 16) at 95% = 2.66)

UNIT	VARIABLE	SOURCE	DEGREES OF FREEDOM	MEAN SOURCE	F VALUE
LOW ENERGY SORTED (MUDFLATS)	MEAN	Between groups	6	2.739	4.534*
		within groups	14	0.605	
	STANDARD DEVIATION	Between groups	6	0.192	0.722
		within groups	14	0.266	
LOW ENERGY SORTED (MANGROVE)	MEAN	Between groups	6	1.060	3.019*
		within groups	14	0.351	
	STANDARD DEVIATION	Between groups	6	0.015	0.262
		within groups	14	0.058	
PRE-SORTING	MEAN	Between groups	7	5.304	47.188*
		within groups	16	.112	
	STANDARD DEVIATION	Between groups	7	1.001	21.531*
		within groups	16	.047	

* Significant differences in the means

significant differences and therefore a calculated F value greater than the 95 percent critical value for the F distribution (given in Table 4) indicates whether differences between localities are significant despite the analytical and sampling errors. Differences are significant (at the 95 percent level) with both the mean and standard deviation values except for the standard deviation values in the low-energy sorting unit. These tests do show, though, that the use of these two variables in future numerical analyses is warranted.

OTHER X-Y PLOTS

Despite the ill-conditioning problem with the skewness and kurtosis determinations, X-Y plots of the other pairs of the four distribution parameters are given in Figure 21. These allow comparison with other studies such as Folk & Ward (1957) and Thomas et al. (1972), and brief comments for each plot are given below.

With each plot the samples from groups B and C from Figure 13 which exemplify the ill-conditioning problem are shown.

Skewness-Mean

Three basic groups are apparent: a central group representing the sand end-member population which shows slightly positive skewness due to the minor silt content; the upper 'hyperbola-like' group consisting of the silt-clay end member population with slightly negative skewness (due to the minor silt content) at one end of the trend and the sand samples with a minor clay mode at the other; and the lower 'hyperbola-like' group trending from positively skewed samples with a dominant gravel and minor sand content to negatively skewed sand samples with minor gravel modes. The plot also points to the non-discriminatory nature of the skewness values. The plot does not correspond to Folk's sinusoidal trend but has some similarities with the plot shown by Thomas et al. (1972).

Mean - Kurtosis

This plot emphasizes the broad two-group sedimentation model previously referred to; the sediments with a mean greater than about 5 phi have negative kurtosis over a narrow range of values due to the bimodal grainsize

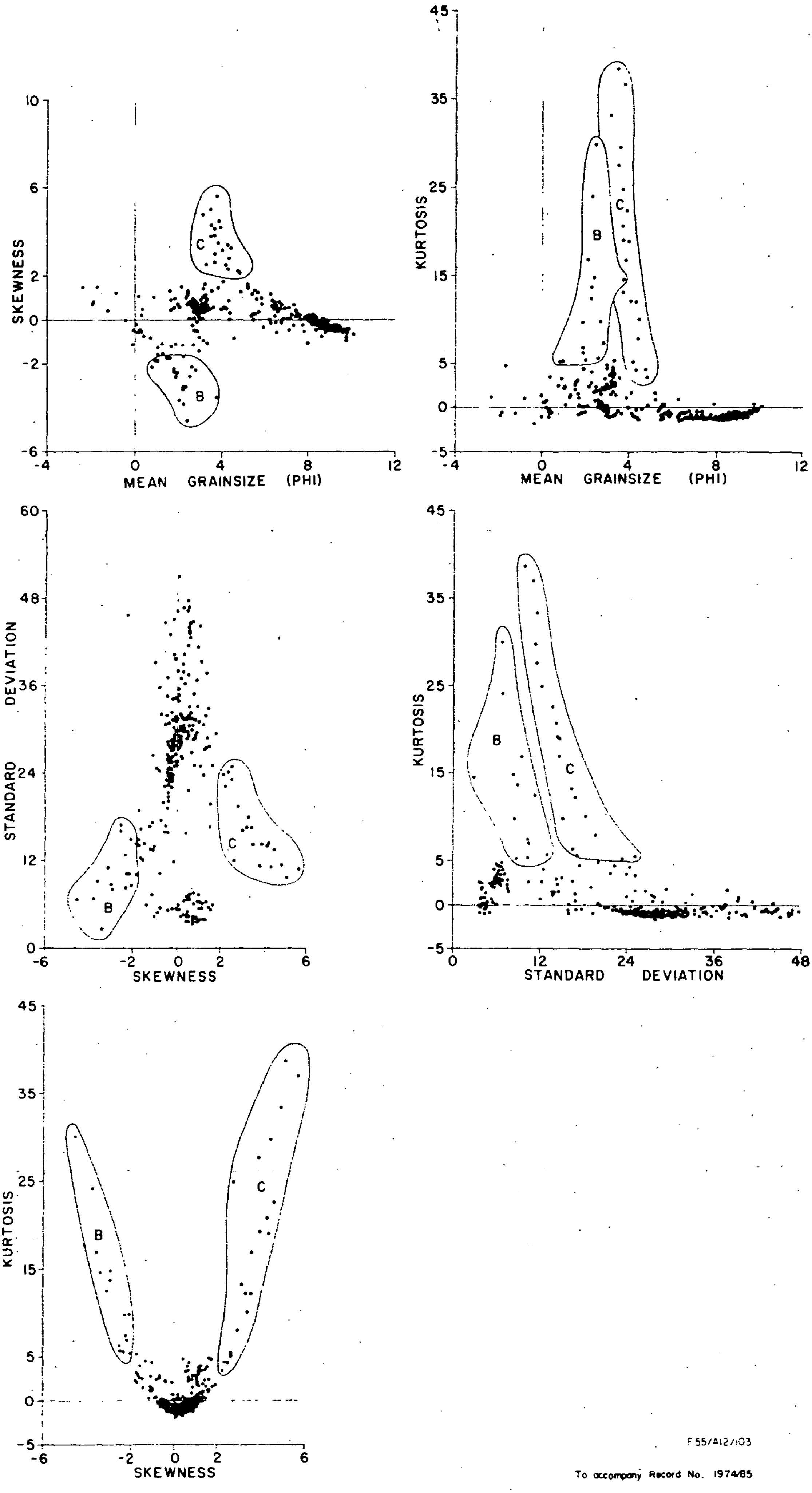

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Fig. 21 Relationships between the four grainsize parameters.

distribution of these samples; and the rest have a broad range of kurtosis values, both negative and positive. Again the plot is similar to that reported by Thomas et al. (1972).

Skewness - Standard Deviation

This plot cannot be used to deduce any more information than has already been obtained from the plots on Figure 13. A circular trend similar to that illustrated by Folk & Ward (1957) did not arise from the Broad Sound values. Folk & Ward argue that the circular trend results with a two-population system: samples with unimodal grainsize distributions have low standard deviations and zero skewness. Those with equal mixtures of the two modes have the highest standard deviations and zero skewness. Higher absolute skewness values (negative or positive) result when one mode is subordinate to the other. These arguments apply to the two end-member populations and the groups B and C (Fig. 21(c)) of the Broad Sound samples, although the samples from the silt/clay population are bimodal. Nevertheless, the plot positions of the two populations plus groups B and C do not approximate a circular trend and the samples with larger standard deviation values than the silt/clay population further destroy any link with a circular trend.

This result reinforces the conclusion that not all the Broad Sound sediments consist of either of the two end-member populations or direct mixtures of them.

Kurtosis - Standard Deviation

With the Broad Sound sediments the samples with the largest standard deviations (greater than about 2) mostly have negative kurtosis. This is understandable as these samples have multimodal grainsize distributions illustrated by Figures 18(b) and 19, resulting in large standard deviations and negative kurtosis. The sand end-member population has zero to slightly positive kurtosis, and the remainder of the samples have positive kurtosis values depending on the position of the fine or coarse minor modes.

Skewness - Kurtosis

A rather striking plot is obtained from skewness and kurtosis; they show a definite quadratic trend which was observed by both Folk & Ward (1957) and Thomas et al. (1972), both of whom consider that the quadratic trend results from the mixing of various amounts of the two end-member populations in their study area. Although this is also relevant to Broad Sound study it may not be the only cause of the trend.

The grainsize distributions of most of the Broad Sound samples have skewness values centring on zero and slightly negative kurtosis values (further indicating the lack of discrimination with these two variables), and a coarse or fine minor mode included with these distributions results in the negative and positive skewness values respectively and the associated positive kurtosis values. For example, the plots in group C in Figure 13 are due to the minor remnants of mud remaining in sorted sand samples, which represent an indirect mixing of the two end-member populations, but the plots in group B are due to the presence of in situ shell material in the high-energy sand bank sediments. This carbonate content then also helps to produce the quadratic trend. The skewness and kurtosis values in groups B and C are of coarse greatly affected by the ill-conditioning problem.

These X-Y plots show how the type of grainsize distribution is represented by its statistical parameters and also emphasize the ill-conditioning problem. Of all the plots, only the mean-standard deviation plot separates the Broad Sound samples into the genetically significant units, and the ill-conditioning of the standard deviation results does not adversely affect this classification, nor the resulting geological interpretations within each unit.

NUMERICAL SAMPLE CLASSIFICATION

Q-Mode Factor Analysis

The sequence of classifying Broad Sound samples into meaningful geological groups so far has been: initial field classification, the grouping of the samples into sedimentary units, and the initial numerical classification from the mean grainsize and grainsize standard deviation values of the samples. Q-mode factor analysis determines sample to sample relationships and has been used to differentiate depositional environments (Klovan, 1966). This technique initially computes the coefficient-of-proportional-similarity (cosine theta coefficient) between each pair of samples, this coefficient being defined as,

$$\cos \theta_{12} = \frac{\sum_{k=1}^{m} x_{k1} \cdot x_{k2}}{\sqrt{\sum_{k=1}^{m} x_{k1}^2 \cdot x_{k2}^2}},$$

where m = number of variables associated with each sample,

x_{k1} = value of k th variable with sample 1,

x_{k2} = value of k th variable with sample 2.

Every element in each eigenvector of the matrix of cosine theta coefficients is multiplied by the square root of the corresponding eigenvalue. The eigenvalues represent the proportion of the total variance (of the cosine theta matrix) accounted for by each eigenvector, and so the result of the multiplication is a set of factors, or vectors, which are weighted in proportion to the amount of variance which each factor explains. These concepts are explained mathematically and intuitively in Davis (1973).

Program CABFAC (Klovan & Imbrie, 1971), which was used in this study, rotates the initial factors to satisfy the varimax criterion (Kaiser, 1958), so that only a few high loadings remain on each factor. Although these mathematical factors need not necessarily represent a geological process, intuitively the factor loadings indicate the effect that a factor has on each sample. The degree of representation of all the factors with each sample is given by the sum of squares of the factor loadings for that sample (the communality). Therefore, differing factor loadings may indicate differing geological effects on the recent Broad Sound samples.

Factor scores which are also produced by CABFAC can be used to interpret the geological significance of each of these factors. The initial factor scores are scaled (by multiplying by the square root of the number of variables) so that the maximum absolute value possible (when all the other variables 'contribute nothing to a factor' and have zero scores) is equal to the square root of the number of variables. 'If all variables in a study are equally important in a factor, then each scaled score equals unity' (Klovan & Imbrie, 1971, fig. 63). Once the important variables for each factor have been found the relationship between them and the corresponding factor can be determined from the relative plot positions of the individual samples and the changing values of the important variables with these samples.

Factor analysis does not assume a knowledge of the distributions nor independence of the variables, but with the Q-mode analysis, transformation of the original data is required so that changes in all the variables have equal weighting (Harbaugh & Demirman, 1964). With this study the values were transformed to the percent of the range of values for each variable.

Further, with the Q-mode analysis, variables which are not independent (for example, measurements of both Ca and $CaCO_3$) give extra weight to the geological processes associated with them. Therefore, variables which were obviously not independent, as well as variables not measured in certain environments or with concentrations below the detection limit, were left out of the analysis. Consequently, 29 variables (Table 5) and 289 samples (as indicated in Table 1) were used in the factor analysis. Although the gravel, sand, and mud percentages are directly related to the mean grainsize measure and are also dependent on each other, they were included as their contribution to the final interpretations was considered more important than these disadvantages. The same closed array problem caused by reporting the mineral group on a percentage basis may also need to be considered when the final interpretations are made.

Results and Interpretations

Three rotated factors account for 91.53 percent of the variance in the cosine theta matrix. Including the fourth factor only an extra 1.74 percent of the variance is explained and the important variables (indicated from the factor scores) for the first three factors do not change. Consequently, three factors seems the ideal number to be used. The effect of these three factors (hopefully representing three geological processes) on each sample can be compared graphically by normalizing the three factor loadings for each sample and plotting the values on a triangular diagram (Fig. 22). The loadings are normalized

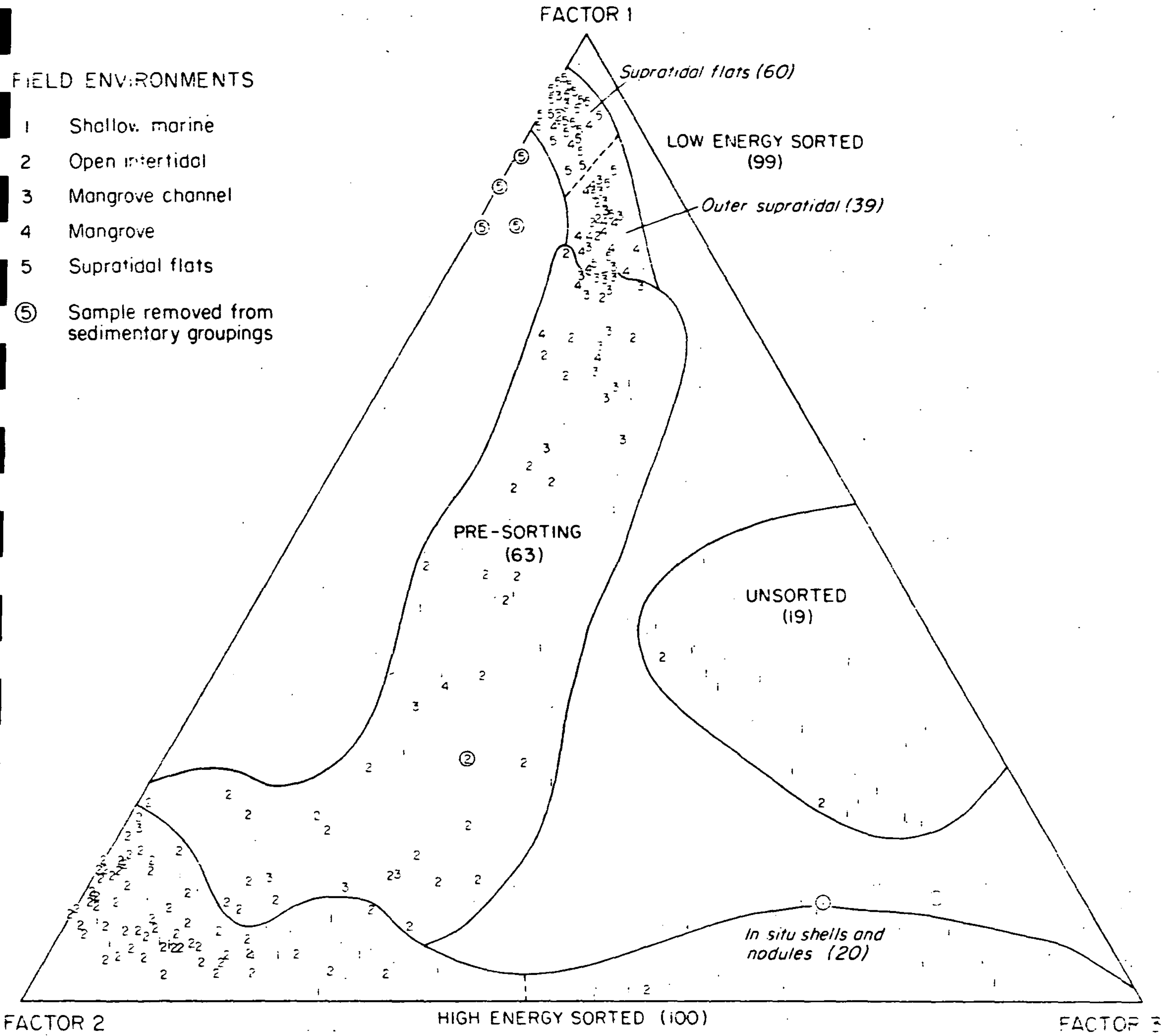

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Fig. 22 Triangular plot of the three normalized factor loadings from the Q-mode analysis.

TABLE 5

Q-MODE FACTOR SCORES

Variable		Factor 1	Factor 2	Factor 3
Mean grainsize		2.14	-0.89	-0.01
Grainsize st. dev.		1.35	0.57	2.03
$CaCO_3$ not removed	% Gravel	-0.23	0.26	1.33
	% Sand	-1.03	-4.13	-0.11
	% Mud	2.83	0.96	0.41
Dolomite		0.10	-0.13	-0.12
Mg-calcite		-0.21	-0.90	1.69
Plagioclase		1.68	-1.18	-1.05
Orthoclase		0.22	-0.74	-0.38
Aragonite		0.07	-1.39	2.10
Quartz		1.21	-1.67	-1.33
Ba		0.32	-0.38	-0.22
Co		0.45	-0.44	-0.31
Cr		0.87	-0.34	-0.13
Cu		0.55	-0.26	0.21
Fe		0.98	0.04	0.06
Mg		0.52	-0.08	0.92
Mn		0.05	-0.27	0.23
Ni		0.78	-0.23	-0.25
Pb		0.58	-0.16	0.13
Sc		0.98	-0.41	0.26
Sr		-0.06	-0.38	0.90
Ti		1.06	-0.38	-0.01
Va		0.52	-0.08	0.12
Y		0.32	-0.80	-0.19
Zn		1.54	0.03	-0.03
Zr		0.15	-0.36	-0.09
$CaCO_3$		-0.49	-0.66	2.79
P_2O_5		0.63	0.20	1.65

Factor "composition"

Factor 1

1. % Mud
2. Mean grainsize
3. Plagioclase
4. Zn
5. Grainsize st. dev.
[illegible] tz

Factor 2

1. % Sand
2. Quartz
3. Aragonite
4. Plagioclase

Factor 3

1. $CaCO_3$
2. Aragonite
3. Grainsize st. dev.
4. P_2O_5
5. % Gravel
6. Quartz

by squaring each loading, multiplying by 100 (percent), and dividing by the communality for that row. The field environment of each sample is also indicated on Figure 22.

Except for only 10 samples, the same samples in each of the sedimentary units plotted as separate groupings on Figure 22. The corresponding sedimentary unit names are indicated. In addition, 8 samples were removed completely from any of the units: samples 45, 58, 131, 153, and 230 because of abnormally high non-carbonate gravel percentages for samples in the associated unit; samples 267 and 310 because of indefinite plot positions; and sample 181 because of excessive mud content. Apart from a few exceptions, then, samples from the previously classified sedimentation units are grouped separately by these three Q-mode factors. The individual samples in each of the sedimentary units are shown in Appendix II and the original classification of these samples reclassified and removed as a result of the Q-mode analysis are indicated. These factors now need to be interpreted geologically to see if the geological reasoning used to specify the four sedimentary units is substantiated.

The scaled varimax factor scores for the 3 rotated factors are given in Table 6. A cut-off value of 1.1 was used to isolate the variables that are important contributors to each factor, and the variables are also given in decreasing order of importance in Table 5. To aid in these interpretations Table 7 shows the means for each of the variables in 6 separate sample groupings from Fig. 22 (the 4 sedimentary units plus the outer supratidal group separated from the low-energy sorted unit and the group of samples with very significant amounts of in situ shells and nodules separated from the high-energy sorted unit).

Increasing factor 1 loadings reflect increasing mud percent, associated with a corresponding increase in mean grainsize (phi) values. This factor then probably represents the low-energy sorting process which results in mud concentrations in the low-energy sorted and the unsorted units. Both Zn and plagioclase also increase with the loadings on factor 1, possibly indicating that silt-sized plagioclase is being produced in the estuary by abrasion (as was suggested earlier), and Zn is concentrated in the clay fraction.

Factor 2 appears to represent the high-energy sorting process, the factor loadings increasing with increasing percent sand and quartz. The low aragonite values in samples from the high-energy sorted unit with no in situ shells or nodules (compared to the unsorted unit and the samples in the high-energy sorted unit with in situ shells and nodules) suggest that aragonite is concentrated in the shells or nodules or both. Extremely low aragonite values in the supratidal flat deposits support this.

The third factor reflects a lack of sorting in samples with in situ shells and nodules or mud-sand-gravel mixtures, the loadings increasing with increasing $CaCO_3$, grainsize standard deviation, and percent gravel. P_2O_5 values increase from the high-energy sorted unit (excluding samples with in situ shells and nodules) to the low-energy sorted unit, with the greatest increase in the unsorted unit and the high-energy sorted samples with in situ shells and nodules. This indicates the important association of P_2O_5 with the shells and nodular material, as well as with the mud fraction. Mg-calcite values are relatively low in the low-energy sorted unit, indicating an association with shells and nodular material in the other units.

The geological interpretations of the three factors coincide with those used in the sedimentation model. Furthermore, these geological processes directly affect the grainsize distributions of the estuarine sediments, thus explaining the similar sample groupings obtained from the grainsize mean/standard deviation plot and the Q-mode factor analysis. No doubt the inclusion of the 3 variables percent gravel, sand, and mud reinforced this effect, but it did not change the basic interpretations; nor did other closed array problems in the result appear to affect them.

Consequently, the triangular plot (Fig. 22) illustrates the expected relationships between the 4 sedimentation units. The pre-sorting unit linking the low-energy sorted and the high-energy sorted units (the boundaries being somewhat indefinite because of the similarity of certain supratidal flat, mangrove swamp, mangrove channel, and open intertidal samples at the low-energy end, and sorted sand samples compared to those still with significant unsorted mud at the high-energy end) and the unsorted unit isolated from the rest. The plot also shows the distinction between the supratidal deposits as well as identification of those samples in the high-energy sorted zone with significant amounts of in situ shells and nodules. The factor analysis also supplies useful information on other variables also affected by the interpreted geological processes.

It is tempting to suggest that the conclusions already reached concerning the sediment movement in Broad Sound could have been obtained by substituting the Q-mode factor analysis for the work on the sedimentation model together with plots of the grainsize distribution parameters. Doubtless, the same amount of geological reasoning and experimentation would have been required to obtain a meaningful geological classification and the associated processes of sediment movement if the factor analysis had been used as the starting point.

Nevertheless, the support given by factor analysis to the previous sample classification and sedimentation model will allow these sample groupings to be used with added confidence and knowledge, when the interrelationships between the variables within each group are being determined.

CONCLUSIONS

The conclusions can be summarized as follows:

1. Using all available grainsize data and other relevant observations four basic sedimentation units can be identified in the Broad Sound sediments

(a) the unsorted unit;

(b) the pre-sorting unit;

(c) the sorted high-energy unit;

and (d) the sorted low-energy unit.

The sorted low-energy unit can be further subdivided into the outer and the inner supratidal zone. A summary of the major differences between the four units is given in Table 7. The sorted high-energy unit includes the terrigenous sand end-member grainsize population, and the sorted low energy unit the terrigenous silt/clay end-member population.

2. The four basic sedimentation units are graphically identified by an X-Y plot of the mean and standard deviation values of the sample grainsize frequency distributions. Skewness and kurtosis values of the same distributions are not useful for classifying the Broad Sound samples and the determination of these values for many of the samples is very ill-conditioned. Within each unit the changes in both mean and standard deviation can be interpreted geologically.

3. This classification and the resulting geological interpretations could only be recognized after the detailed sedimentation model for this study area had been proposed.

4. Therefore, the two grainsize distribution parameters mean and standard deviation may be used to classify the samples genetically so that detailed studies on the inter-relationships of variables within each unit can be carried out. The geological interpretations associated with the mean and standard deviation changes within each unit can be used to clarify these inter-relationships.

5. Results of a Q-mode factor analysis support this genetic sample classification and the related geological processes, and also supply useful information on the variables affected by these processes.

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APPENDIX I

Statistical Moment Measures

The mean for grainsize data, x, is defined as,

$$x = \frac{1}{100} \sum_{i=1}^{h} x_i f_i \quad \text{(phi)}$$

where h = number of grainsize class intervals

x_i = mid-point of the class interval

f_i = frequency percent in the i th class interval

The other three statistical measures are determined using the second, third and fourth moments about the mean. This 'moment about the mean' concept for grainsize data is defined as

$$m_k = \frac{1}{100} \sum_{i=1}^{h} (x - x)^k f_i$$

where m_k = k th moment about the mean

Variance = m_2

Standard deviation, S, = $\sqrt{m_2}$ (phi units)

Skewness, g, = $\frac{m_3}{S^3}$ (dimensionless)

Kurtosis, g_2 = $\frac{m_4}{S^4} - 3$ (dimensionless)

APPENDIX II

Sample Classification Into Sedimentary Units

Unsorted	Pre-sorting		High-Energy Sorted			
196	97	236	61	314	137	316
198	219(U)	251	66	315	144	INT 320
215	237(U)	260	67	MAR 317	145	326
218	239	272	72	36	151	MAC 327
220	246(U)	283	79	37	154	
241	262(U)	INT 297	80	41	156	
242	271	323	87	42	187	
263	285	325	88	47	188	
264	MAR 318(U)	331	89	49	202	
273	4	332	96	50	209	
286	9	335(LE)	99	53	211	
287	10	336	101	54	213	
295	20	337	195	55	222	
308	21	339	197	56	223	
309	26	342	199	57	226	
311	27	344	201	59	238	
MAR 319	31	345	216	60	247	
INT 363	40	346	217	62	248	
	48	347	221	68	249	
	71	348	243	69	250	
	74	349	244	73	261	
	76	350	245	75	274	
	81	351	268	82	280	
	83	352	269	90	281	
	108	353	270	92	282	
	109	354	289	98	284	
	111	MAC 356	290	100	294	
	128	174	291	114	296	
	141	252	292	121	198	
	150	255(LE)	293	129	304	
	214	MAS 299(LE)	312	134	305	
	224		313	136	306	

Low-Energy Sorted

Outer-supratidal zone		Mudflat zone		Remainder
				267(U)
				MAR 310(U)
30	MAS 321	MAC 334	148	58(HE)
122	2	84	149	INT 181
138	103	146	166	45
INT 229	107	303	167	131
324(P)	162	MAS 322	168	158
329	189	14	169	SUP 230(LE)
330	253	19	172	
333	SUP 279	22	173	
338		32	175	
340		34	176	
341		38	179	
343		39	182	
MAC 355(P)		44	183	
212		52	184	
MAI 225		64	190	
35		70	191	
43		77	192	
46		85	193	
102		86	204	
123		94	205	
127		104	206	
140		112	108	
143		116	210	
147		119	231	
180		120	232	
203		124	234	
227		130	277	
228		132	300	
235		133	SUP 302	
275		139		
276		142		

Legend:

Symbols in brackets indicate previously classified unit

U - unsorted
P - pre-sorting
HE- High energy sorted
LE- low energy sorted

The original field classification is also shown beside the last sample of that field environment in the unit.

MAR - Shallow Marine

INT - Open Intertidal

MAC - Mangrove channel

MAI - Mangrove Swamp (intertidal zone)

MAS - Mangrove Swamp (supratidal zone)

SUP - Supratidal flats