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Sediment Properties off Broome, Port Hedland & Darwin

P. J. Mulhearn and A. Cerneaz

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Abstract

To investigate the likelihood of mine burial by various mechanisms in northern and north-western port approaches, sea floor sediment samples were obtained on a number of research cruises off Broome, Port Hedland and Darwin. In this report the results of analyses on these samples, to obtain a range of relevant sediment properties, is presented. The mine burial estimates derived from these results will appear in a companion, classified report. The sea floor in the approaches to both Broome and Port Hedland consists predominantly of carbonaceous sand, and off both these ports the bottom is so hard at a significant number of locations that only small sediment samples were obtainable, even after several attempts with a grab. In the approaches to Darwin the most common surface sediment type is muddy sand, however there are also broad areas of sandy gravel, gravelly sand and sand, and at some locations there is a shallow surface sand layer underlain by a more muddy one.

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Sediment Properties off Broome, Port Hedland & Darwin

1. Introduction

Sediment sample data have been obtained, on a number of cruises, in the shallow water approaches of Broome, Port Hedland and Darwin. These three ports, especially the first and the last, are priority ports for both Australia's defence and her overseas trade. A search of the literature showed that very little information was available on sea floor properties near these ports, for water depths less than 40 m. This can be seen, for example, in the survey of Harris et al. (1991). The sediment surveys were undertaken to obtain sea-floor data in order to determine the most significant mine burial mechanisms in our northern and north-western approaches. This is useful firstly for planning mine-counter-measures operations and exercises, but secondly as a guide to the most relevant directions for future research into mine burial mechanisms and modelling. The results of the sediment analyses are also relevant to mine-hunting sonar, for the estimation of acoustic backscatter from the sea- floor, and to diver and remotely operated vehicle operations, for the estimation of underwater visibility ranges. Results of the sediment analyses are presented in this report and the inferences for mine burial are discussed, separately, in Mulhearn (1993a).

At all three locations tidal currents are strong and spring tide heights have ranges of 8.5 m, 5.5 m and 7.8 m at Broome, Port Hedland and Darwin, respectively. The overall area has a tropical, monsoonal climate. There is a dry season from approximately late April to September, with predominantly south-east winds, and a wet season from approximately December to March with light, variable winds, except for the occasional tropical cyclone. Cyclones generally occur between December and April, but are most likely in January or February. On average there are ten cyclones per decade in the Timor Sea, but only approximately half these cross the coastline. More about Australia's North - West can be found in Granger (1990), and about Darwin Harbour in Larson et al. (1988).

2. Research Cruises, Methods and Equipment.

Sediment samples were obtained on the cruises and with the equipment listed in Table 1. Station positions are listed in Appendix A. The work done from M. V. Malita mostly covered surface sediments further offshore, but six samples were obtained off Darwin in the same area as covered by our 1990 and 1992 cruises. Malita's results are presented in van Andel and Veevers (1967) and Jones and Burgis (1974).

HMAS's Bunbury, Geraldton and Dubbo are patrol boats. HMAS Cook was an oceanographic research vessel and LCM-8 is a Landing Craft Medium. The Van Veen grab, used off Broome and Port Hedland, had a catcher which was 0.305 m long, 0.23 m deep and 0.305 m wide at its widest point. Off Port Hedland in February 1992 a Birge-Ekman grab was used for sampling until it broke, and then the Van Veen grab was used. The box on the Birge-Ekman grab was 0.20 m deep and had a 0.15 cm x 0.15 cm cross-section. The large box-corer used off Darwin in February and March 1990 had a box which was 0.6 m deep, and 0.2 m x 0.3 m in area. Shear strength measurements were done on the box-cores at sea and cylindrical cores (internal diameter 69 mm) taken from these for later laboratory analyses. The grab samples from all cruises and the cylindrical cores from HMAS Cook were stored in a cool-room or refrigerator soon after they were obtained and detailed analyses performed on them back in the laboratory. Stations with their positions and the results of sediment analyses are tabulated in the appendices. On all cruises, except that on HMAS Cook, grabs were deployed by hand. In many cases the sea floors encountered were quite hard and several attempts were necessary to obtain a sediment sample. In such cases the amount of sediment obtained was small. It is not clear, without further data, if these difficulties were due to hard packed sediment or rocky areas with a thin sediment cover.

The shear strength profiles measured at sea on box-cores were obtained using a vane shear test device (Monney, 1971). This consisted of two square brass vanes, arranged in a cross, with faces perpendicular to each other and to the sediment surface. This cross was attached to the end of a long brass rod. The vanes were pushed into the sediment and rotated by hand till failure occurred. The torque at which this happened was measured with a torque wrench used as a handle on the end of the brass rod. The device was inserted to a number of depths to obtain a shear strength profile. While at sea, average densities were also obtained of the cylindrical cores, taken from the box-cores, using their weight and volume.

Table 1: *Summary of Research Cruises*

Date	Location	Vessel	Equipment
Nov/Dec60	Off Darwin	M. V. Malita	Short gravity core
Dec90	Off Broome	HMAS Bunbury	Van Veen grab
Dec 90	Off Port Hedland	HMAS Geraldton	Van Veen grab
Feb/Mar 90	Off Darwin	HMAS Cook	Large box-corer
Feb 92	Off Port Hedland	HMAS Dubbo	Van Veen & Birge - Ekman grabs
Feb 92	Off Darwin	LCM-8	Birge - Ekman grab

3. Laboratory Analyses

3.1 Parameters Obtained and Their Usefulness

Laboratory analyses carried out on all sediment samples were:
Gravel/sand /mud percentages;
Determinations of porosity and sediment grain density (from which sediment bulk densities were found);
Carbonate percentages in sand and mud fractions;
Colour.

Laboratory analyses carried out on many but not all samples were:
Grain size distributions by sieving (most samples were largely sand and gravel), from which means and standard deviations of sediment grain size were found;
Angle of initial yield (that at which grains in a gradually tilted specimen first start to move).
See Appendices A and B for sediment analyses and sample descriptions, respectively.

Some of these parameters merely provide a broad description of the sediments, while others are more directly useful for mine burial estimates. Mean sediment grain size, grain size distribution, and grain density are important sediment properties for the estimation of mine burial by scour. For estimating impact burial (the depth to which a mine is buried when it strikes the sea floor at deployment) the most important sediment property is the shear strength profile as a function of depth. The sediment density profile also has some effect, but is less important (Satkowiak, 1988). At all sampling stations off Broome and Port Hedland, and at the majority of those off Darwin, only near surface samples are available, however it was found that at most stations surface sediments are hard and coarse (see below) and impact burial is expected to be small. An estimate of shear strength can however be obtained from the angle of initial yield, because this is usually identified with the friction angle, ϕ_{fr} used in soil mechanics (Sleath, 1984). For granular sediments, shear strength τ is given by:

$$\tau = \sigma \tan \phi_{fr},$$

where σ = normal stress i. e. stress acting at right angles to the plane along which shear stress is being applied. Where sediment density is constant with depth:

$$\sigma = (\rho_{sed} - \rho_w)\, g\, z,$$

where ρ_{sed} = bulk sediment density,
ρ_w = water density,
z = depth below the water-sediment interface,
and $\tau(z)$ can then be determined.

Sediment properties affect other aspects of mine counter-measures operations, e. g:

- sediment porosity and grain size are significant for the determination of levels of sea floor backscatter to mine-hunting sonars;

- sediment colour influences the visual contrast between a mine and its background and so affects diver and remotely operated vehicle (ROV) operations;
- sediment grain density and grain size distribution influence the ease with which sediment is entrained into the water column, which can reduce visibility and this also affects diver and ROV operations.

3.2 *Grain Size*

In the laboratory, grain size analyses were carried out on each sample by sieving them into gravel, sand and mud size fractions, using 2.0 and 0.063 mm sieves. These fractions were oven dried, weighed and the percentages of each determined. Here the terms gravel, sand and mud are used to describe particle sizes, not chemical composition. In standard geological terminology *gravel* means particles too large to pass through a 2.0 mm sieve, *sand* means particles which can pass through a 2 mm sieve but not through a 0.063 mm sieve, and *mud* means particles which can pass through a 0.063 mm sieve. In marine sediments gravel usually consists of broken up pieces of shell (chemical composition $CaCO_3$) and sand also often has a high carbonate content.

In this report sediments are classified, according to the proportions of gravel, sand and mud they contain, using a triangle similar to that of Shephard (1954) for sand, silt and clay. See Fig. 1.

The percentage of gravel or sand or mud decreases from 100 to 0 as one moves, respectively, from the "gravel" or "sand" or "mud" vertex to the side opposite it. The sides of the triangle represent mixtures of only two components: gravel and sand, sand and mud, and mud and gravel.

Grain size distributions were obtained by standard sieving techniques (Folk, 1980), using dry sieving for coarser size fractions and wet sieving for finer. Samples were separated into the following fractions:

pebbles	diameter > 4 mm,	$\phi < -2$;
granules	diameter = 2 to 4 mm,	$-2 < \phi < -1$;
very coarse sand	diameter = 1 to 2 mm,	$-1 < \phi < 0$;
coarse sand	diameter = 0.5 to 1 mm,	$0 < \phi < 1$;
medium sand	diameter = 0.25 to 0.5 mm,	$1 < \phi < 2$;
fine sand	diameter = 0.125 to 0.25 mm,	$2 < \phi < 3$;
very fine sand	diameter = 0.063 to 0.125 mm,	$3 < \phi < 4$;
coarse and medium silt	diameter = 0.016 to 0.063 mm,	$4 < \phi < 6$;
fine silt and clay	diameter < 0.016 mm,	$\phi > 6$;

where $\phi = -\log(\text{diameter in mm})/\log(2)$. From these data, cumulative size distributions versus ϕ were constructed in order to obtain Graphic Mean sediment sizes (M_z) and Inclusive Graphic Standard Deviation (σ_1), defined by Folk (1980) as:

$$M_z = (\phi16 + \phi50 + \phi84)/3, \text{ and } \sigma_1 = (\phi84 - \phi16)/4 + (\phi95 - \phi5)/6.6,$$

where ϕXX is the ϕ-size at which a particle cumulative size distribution is XX% i.e. that for which XX % of a sample has particle sizes larger than ϕXX (e.g. $\phi16$ is the size for which 16 % of a sample consists of particles larger than $\phi16$). As discussed in Folk(1980) M_z and σ_1 are the best measures of the mean and standard deviation of grain size. σ_1 is used as a measure of how well sorted a sediment is (Folk, 1980), so:

$\sigma_1 < 0.35\phi$,	very well sorted	$1.0 - 2.0\phi$, poorly sorted
$0.35 - 0.50\phi$,	well sorted	$2.0 - 4.0\phi$, very poorly sorted
$0.50 - 0.71\phi$,	moderately well sorted	$> 4.0\phi$, extremely poorly sorted.
$0.71 - 1.0\phi$,	moderately sorted	

In some cases $\phi 95$ and/or $\phi 5$ could not be determined because so much of the sample was either fine silt and clay or pebbles, then the Graphic Standard Deviation, σ_G (Folk, 1980) was calculated, where:

$$\sigma_G = (\phi 84 - \phi 16)/2.$$

In a very few cases only the Median diameter ($M_d = \phi 50$) could be calculated.

3.3 *Sediment Porosity and Density*

Sediment porosity and grain density were measured as described by Baker et al. (1988). Porosity is defined as the ratio of the volume of water between the grains in a sediment sample to the total volume of the sample. It is obtained by weighing a sample of sediment when it is saturated with water and when it has been thoroughly dried out, and using the formula:

$$n = W_w \,/\, (W_w + W_s(\rho_w/\rho_s)),$$

where n = porosity,
W_w = weight of water,
W_s = dry weight of sediment,
ρ_w = density of water and
ρ_s = grain density of sediment, which was obtained as described below.

From the above formula and the relation:

$$n = (\text{Volume of water}) / (\text{Sediment volume}) = (W_w \,/\, \rho_w)/((W_w + W_s)/\rho_{sed}),$$

where ρ_{sed} = sediment bulk density, one can obtain:

$$\rho_{sed} = \rho_s + n\,(\rho_w - \rho_s).$$

Sediment grain densities were found by obtaining grain specific gravities, using Archimedes' Principle (Baker et al., 1988). The following were measured:

w, the weight of an empty sample bottle;
x, the weight of the bottle filled with water;
y, the weight of a dried and crushed sediment sample;
z, the weight of the sample bottle with the sediment sample in it and filled with water.

The weight, W, of water occupying the same volume as the sediment sample is:

$$W = (x - w) - (z - w - y),$$

and specific gravity, G, of the dry sample, or sediment grain specific gravity, is:

$$G = y/W,$$

and grain density is given by:

$$\rho_s = \rho_w G.$$

3.4 Other Properties

The carbonate content of the gravel, sand and mud fractions was analysed using an "acid bomb" (Muller and Gastner, 1971). This is a small enclosed volume in which hydrochloric acid is mixed with a sediment sample, and the measured increase in pressure is proportional to the amount of CO_2 released, which in turn is proportional to the amount of carbonate originally present in the sample. For sediment samples off Broome visual inspection indicated that the gravel fraction was 100% carbonate, and there was no need to use the "acid bomb." From these results the percentage of carbonate in the whole sample was determined.

Angle of Initial Yield was estimated using a circular tube, with its axis horizontal, partly filled with the sediment sample, and topped up with water. The cylinder was rotated to find that angle at which grains first began to move, which is the angle of initial yield (Carrigy, 1970).

The colour of the wet sediment was determined using the Rock Color Chart published by the Geological Society of America.

4. Results

4.1 Broome

The gravel/sand/mud triangle for Broome is shown in Fig. 2. The percentage of mud in these sediments is very low and the samples fall into the three categories of sandy gravel, gravelly sand, and sand. The spatial distribution of these bottom types is shown in Fig. 3. It can be seen that the bottom consists of sand at most stations. A more exact determination of the geographical extent of sandy gravel and gravelly sand areas cannot be determined without obtaining additional data. The only other data from near Broome, known to the author, is in Wright (1981) who, in an investigation of beach dynamics, reported fine sand with $M_Z \cong 2.8$ (in ϕ units) and 60 to 75% carbonate content near 17° 57'S, 122° 12'E. In Fig. 4 the stations at which the bottom was hard and grab samples were difficult to obtain are indicated. Most are on sandy bottoms. As stated previously, these may be areas of hard packed sediment or areas with only a thin sediment cover. Given the high tidal currents (2 to 3 knots) near Broome, the latter is quite possible.

The spatial distribution of the percentage of carbonate in whole samples (i. e. gravel, sand and mud combined) is shown in Fig. 5. (It was assumed that the gravel fraction was 100 % carbonate). Carbonate is a maximum in the shallow area, less than 10 m deep, south-west of Ganheaume Pt. and decreases from there as one moves north-west. Within this area are the Pearl Shoals, which are described in the Australia Pilot (Hydrographer of the Navy, 1972) as "composed mainly of sand and mud, with occasional strips of dark sandstone" and as having "general depths of less than 5.5 m". (The terms sand and mud used here would have their common meanings, not the geological ones. No samples were taken on Pearl Shoals). The area is apparently one with high biological production of carbonate, e. g. by coral reefs, pearl shells, forams, etc.

The spatial distribution of sediment porosity is shown in Fig. 6. The variation in porosity is not large and the contour pattern on Fig. 6 may be altered significantly by the addition of more data.. The difference between the two values, obtained close together south of Ganheaume Point, suggests that porosity can vary measurably within a relatively small area. Also the contour pattern in Fig. 6 bears no resemblance to those in Figs. 3 or 5, suggesting that a denser grid of sampling stations would give a quite different pattern for porosity. Richardson and Briggs (1993) examined the variability of a number of surface sediment physical and geoacoustic parameters from replicate samples taken within a 100 m radius. They did this at 23 different sites. For porosity the ratio of its standard deviation to its mean (i. e. its coefficient of variation, CV) ranged from 1.6% to 28.4%.

The best way to use these results is to take the porosity, n, as not varying greatly over the area, and use the sample values to obtain statistics for its variability. See Table 2. Similarly no clear spatial patterns were found for values of angle of initial yield, ϕ_i, sediment grain density, ρ_s, sediment bulk density, ρ_{sed}, or mean grain diameter, M_z. Statistics for their variations are also presented in table 2. Richardson and Briggs (1993) found that the CVs for ρ_{sed}, within an area with a 100m radius, ranged from 1.0% to 19.8% over their 23 different sites. For M_z, CVs ranged from 2.1% to 81.6%.

Histograms of the values of porosity, angle of initial yield and grain density are shown in Figs. 7, 8 and 9, respectively. It can be seen that the histograms for porosity and grain density are quite skewed, explaining the observed difference between mean and median values for these parameters. The histogram for grain density shows no clear maxima, and is rather flat.

Regression relations between various parameters were investigated, and ones with correlation coefficients greater than 0.5 are presented here. Whole sample carbonate percentage showed some correlation with M_z (correlation coefficient, r, of 0.52) indicating that as M_z increases (i. e. average grain size in mm decreases) carbonate percentage decreases (See Fig. 10). This implies that larger particles are more likely to be carbonaceous.

Grain density increases with porosity (r = 0.94), as shown in Fig 11, implying that sediments with denser grains are less well packed. Particles of shell would tend to occur as laminae and could pack more closely together than particles with a spherical or ellipsoidal shape. This regression suggests that particles with higher densities are more nodular than laminar. The correlation coefficient between particle size and porosity is low (r = 0.18) so there is little connection between these two variables, and by inference between particle density and size.

An interesting relation was found between the degree of sorting in samples, as measured by σ_1, and angle of initial yield, ϕ_i, as shown in Fig. 12. As ϕ_i increases σ_1 decreases at first and then increases, so that the regression relation is a quadratic. It has r = 0.88. Statham (1974) found that the angle of repose increased (and porosity decreased) as sorting became poorer (i. e. as σ_1 increased). The angle of repose, ϕ_r, is the angle from the horizontal taken up by a sediment surface when it has come to rest after being tilted beyond its ϕ_i. Statham explained the increase of ϕ_r with σ_1 as due to finer materials filling in the spaces between larger grains, giving a more stable structure. One would expect ϕ_i to behave similarly, i. e. ϕ_i to increase with σ_1. It is not clear why the opposite occurs for lower ϕ_i values, i. e. why poorer sediment sorting results in a less stable structure in some cases. It is interesting that a quadratic relation was also found at Port Hedland and Darwin (see below). At Broome there was little correlation between whole sample carbonate percentage and angle of initial yield (r = 0.13).

At Broome porosity initially decreased as σ_1 increased and then appeared to become constant as shown in Fig. 13. (The quadratic regression line through the points has r = 0.89). Statham (1974) also found that porosity decreased as sorting became poorer, but at an increasing rate.

***Table 2:** Statistics of some sediment properties off Broome*

	n	ϕ_i (degrees)	ρ_s (gm/cc)	M_z (ϕ units)	ρ_{sed} (gm/cc)
No. of observations	24	24	24	10	24
Minimum	0.44	25.0	2.25	-0.23	1.65
Maximum	0.59	41.4	3.00	2.30	2.01
Mean	0.51	35.7	2.72	0.94	1.83
Standard deviation	0.04	4.0	0.19	0.79	0.09
Standard error of mean	0.01	0.8	0.04	0.25	0.02
Median	0.50	36.2	2.75	0.90	1.83

4.2 Port Hedland

The gravel/sand/mud triangle for Port Hedland is shown in Fig 14. The muds were all found in the dredged approach channel to Port Hedland, in the area where water depths outside the channel were less than 10 m. Bottom composition appears to be very patchy in the approach channel in this area because muddy sands, sands and sandy gravels were also encountered, and the bottom was hard in places with several attempts having to be made to obtain sea-floor samples. Sediment deposition rates for 1970 to 1973 in the dredged channel, and some bottom samples from it are discussed in Paul and Lustig (1975). Further dredging and other changes to the port since 1973 appear to have changed the bottom sediments in the dredged channel, because it is hard to relate our findings to theirs. Of the three muddy sand samples, one came from the dredged channel and two from near 20° 10'S, 118° 30'E, an area which has shallower waters to its north, south and east, and may therefore be sheltered. All other bottom samples were a mixture of sand and gravel and all had less than 15 % mud. Sand was the dominant bottom type. Fig 15 shows the geographical distribution of these bottom types, but no attempt has been made to contour the nearshore part of the dredged channel. (Water depths outside the channel in this area were too small for safe operations). As can be seen, the sea floor is mainly sand, with patches of other bottom types. The real size of these patches cannot be determined without additional information. In Fig 16 the sites are presented at which the bottom appeared to be hard and grab samples were difficult to obtain. It seems that over much of the area off Port Hedland the sea floor is either packed hard or the sediment cover is very thin. Tidal currents here are strong, up to approximately 1 knot at spring tides, but less than those near Broome.

By visual inspection, the gravel fraction off Port Hedland did not appear to be 100 % carbonate, and its carbonate content has not been measured. The carbonate content of the sand fraction is shown in Fig 17. It can be seen that carbonate percentage is high offshore and decreases towards the shallower areas to the south and east, i. e. shorewards, where one would expect an increase in terrigenous sediments. The reason for the decrease in carbonate towards the west is not known.

Statistics for other sediment properties are shown in table 3. As for Broome the apparent patchiness of these parameters made contouring of their geographical distribution very difficult, if not impossible. Histograms for porosity, angle of initial yield and grain density are shown in Figs 18, 19 and 20, respectively. None are particularly similar to their counterparts from Broome (see Figs 7, 8 and 9).

Regression relations between various parameters were investigated and ones with correlation coefficients greater than 0.5 are presented here. The correlation between carbonate percentage and M_z at Port Hedland was 0.63, and again carbonate percentage tended to decrease as average grain size decreased. The linear correlation between grain density and porosity at Port Hedland was low (r = 0.23). The regression curve between sorting, as measured by σ_1, and angle of initial yield is again a quadratic (this time with r = 0.71) and is similar to that from Broome, as can be seen from a comparison of Figs 12 and 21. The regression of porosity against σ_1 suggests that porosity decreases as σ_1 increases (r = 0.32). However in Figs 21 and 22 the number of points is small and the scatter large so little confidence can be placed in these results.

***Table 3:** Statistics of some sediment properties off Port Hedland*

	n	ϕ_i (degrees)	ρ_s (gm/cc)	M_z (ϕ units)	ρ_{sed} (gm/cc)
No. of observations	63	23	63	10	63
Minimum	0.37	29.25	2.09	-1.39	1.31
Maximum	0.71	42.21	3.34	2.75	2.19
Mean	0.48	36.41	2.66	1.03	1.86
Standard deviation	0.06	3.25	0.17	1.44	0.14
Standard error of mean	0.01	0.68	0.02	0.46	0.02
Median	0.48	36.63	2.64	1.22	1.86

In calculating statistics for M_z a value from a muddy sand site (# 45) with $M_z > 3.0$ was omitted. The actual value of M_z was not found because of its high fine silt and clay content.

4.3 Darwin

Surface sediments in the approaches to Darwin have a higher mud content than those of either Broome or Port Hedland, as can be seen by comparing Darwin's gravel/sand/mud triangle (Fig. 23) with those from the other two ports. There is only one station at which sandy mud was found, but there were fifteen where muddy sand was encountered. Muddy sand is the commonest bottom type in this area (35% of samples), while the three bottom types gravelly sand, sand and muddy sand together make up 77% of samples. There is a concentration of points near the gravelly sand/muddy sand boundary in Fig 23, i. e. a lot of samples have a high sand content, with approximately equal amounts of gravel and mud. The gravel fraction is largely made up of broken shell. The geographical distribution of surface sediment types is shown in Fig 24. Additional sampling may change the contours on this map, because it is not clear how patchy the distribution of sediment types is. North of Cox Peninsula, near 12° 20'S, sediment type varies greatly over quite a short distance. Samples from November/December 1960, February/March 1990 and February 1992 were used in Fig 24, as if the sediment distributions did not change with time, but this may not be true. However exclusion of the 1960 points would not change Fig 24 significantly. Michie (1987) contains a map of sediment types for Darwin Harbour and the area very close to it. There is little overlap between his data and ours, and he reports "lime sands and gravels" near 12° 20'S, 130° 50'E and closer inshore.

On Fig 25 are shown locations where the bottom appeared to be hard and several attempts were required to obtain a bottom sample. From Fig 24 it can be seen that the sea floor at two-thirds of these (six out of nine) was gravel or sandy gravel. Also shown on Fig 25 are locations at which a thin, surface layer of yellowish muddy sand or sand was underlain by a green-grey layer with a higher mud content. In smaller grab samples layering would not have been apparent even if it were present, so that one can only say that at some locations the surface sediments form only a thin layer of a few centimetres, over a deeper layer with different properties.

Over most of the area covered off Darwin percentage carbonate in the mud fraction was 20 % to 30 %, except for four isolated stations. However in the area to the north-west, north of 12° 11'S, mud carbonate percentages were 30% or more. It appears that the mud fraction is largely terrigenous and dispersed over a large region offshore. This conclusion is supported by the high turbidities found off Darwin from close inshore to well out to sea (Mulhearn, 1993). The distribution of carbonate percentage in the sand fraction is shown in Fig 26. Percent carbonate generally increases towards the north, and from west to east. North of approximately 12° 18' S the sand fraction is largely carbonaceous. In other words terrigenous sand-sized particles are not dispersed very far offshore.

Histograms for porosity, angle of initial yield, and grain density are shown in Figs 27, 28 and 29, respectively. These are all different from their counterparts at both Broome and Port Hedland. Statistics for porosity, angle of initial yield, grain density, M_z and bulk sediment density for Darwin are presented in Table 4.

Correlation coefficients between carbonate percentage and M_z, and between grain density and porosity were both low at Darwin (0.32 and 0.38, respectively). This is different to the situations found at Broome and at Port Hedland. The regression curve between sorting, as measured by σ_1, and angle of initial yield is shown in Fig 30. It has a similar shape (quadratic with r = 0.49) to those from Broome and Port Hedland, but the number of available points is low. The regression line for porosity versus σ_1, shown in Fig 31, again shows a decrease of porosity as σ_1 increases (r = 0.60), but the number of data points is again small.

Box cores were obtained at each sediment sampling station in February/March 1990, and shear strength profiles obtained at stations 23 and 25 (See Fig. 25 for locations), which had quite muddy sediments (see the end of Appendix A). Cylindrical cores taken from the box cores at stations 23 and 25 were 0.36m and 0.32 m long, respectively. At station 23 the surface sediment was sandy mud, but was muddy sand from 0.05 to 0.36 m. At station 25 the sediment was a muddy sand at the surface, was a gravelly sand from 0.195 to 0.22 m, and a sandy gravel from 0.305 to 0.32 m. However the muddy sands and gravelly sands at station 25 were all close to the boundary, on the gravel/sand/mud diagram, between these two sediment types. The two shear strength profiles are shown in Fig 32, and are very similar. They are probably typical of the muddier areas off Darwin.

Table 4: *Statistics of some sediment properties off Darwin*

	n	ϕ_i (degrees)	ρ_s (gm/cc)	M_z (ϕ units)	ρ_{sed} (gm/cc)
No. of observations	36	36	36	12	36
Minimum	0.31	19.89	2.21	-0.21	1.52
Maximum	0.66	45.28	2.78	3.30	2.08
Mean	0.51	35.50	2.50	1.38	1.74
Standard deviation	0.07	6.31	0.13	1.02	0.14
Standard error of mean	0.01	1.05	0.02	0.29	0.02
Median	0.50	35.93	2.48	1.18	1.76

4.4 Combined Regressions

Because of the small number of points at each port in both the sorting versus angle of initial yield and the porosity versus sorting regressions, data from all three areas were combined to see if results could be obtained, which were not site specific. The outcomes are shown in Figs 33 and 34, respectively. In each case the scatter is too large for these regressions to be useful.

5. Summary of Main Findings

The sea floor in the approaches to Broome consists predominantly of carbonaceous sand, with patches of gravelly sand. Similarly off Port Hedland the bottom is mainly carbonaceous sand, but with patches of both gravelly sand and sandy gravel. Off both these ports the sea floor was so hard at a significant number of locations that only small sediment samples were obtainable, even after several attempts with a grab. In the approaches to Darwin there is more mud in the sea floor, and the most common surface sediment type is muddy sand. However there are also broad areas of sandy gravel, gravelly sand and sand. The sand fraction is again mainly carbonaceous, but the mud is terrigenous. At some locations off Darwin there is a shallow surface sand layer underlain by a more muddy layer.

The tables and figures in this report provide the quantitative data required for estimates of mine burial by various mechanisms.

6. Acknowledgments

The sediment samples from the DSTO cruises were collected with the help of Messrs J. Boyle and M. Savage, who also helped with some of the sediment analyses. Thanks are due to the officers and men of HMAS's Bunbury, Geraldton, Cook and Dubbo and of LCM-8 for their assistance.

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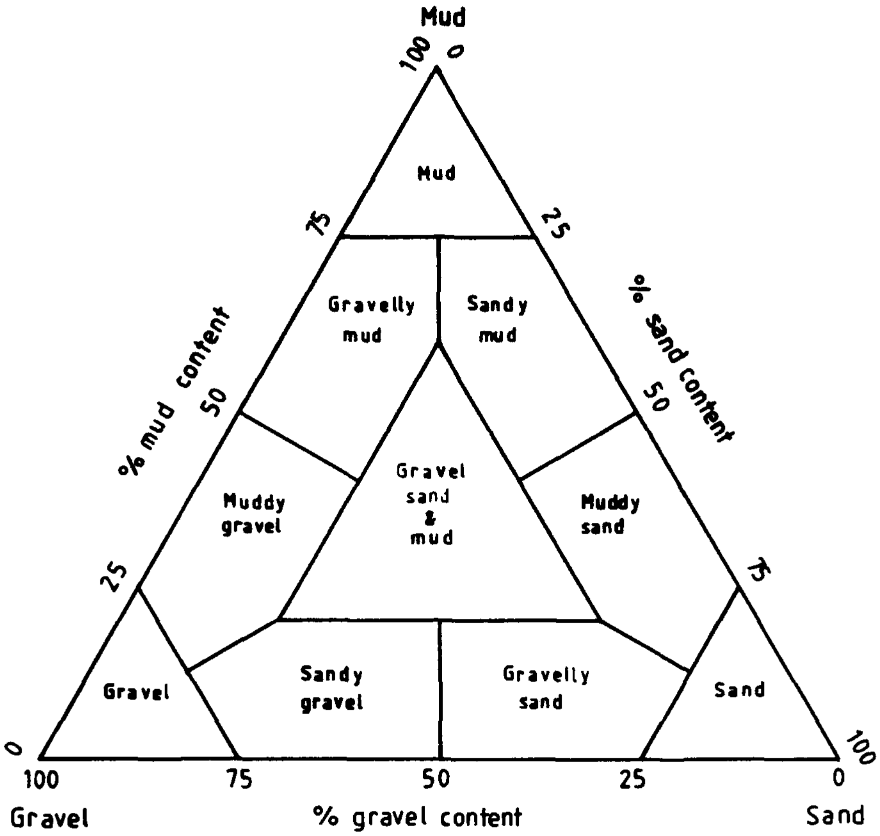

Figure 1: *Gravel/sand/mud triangle showing different sediment types.*

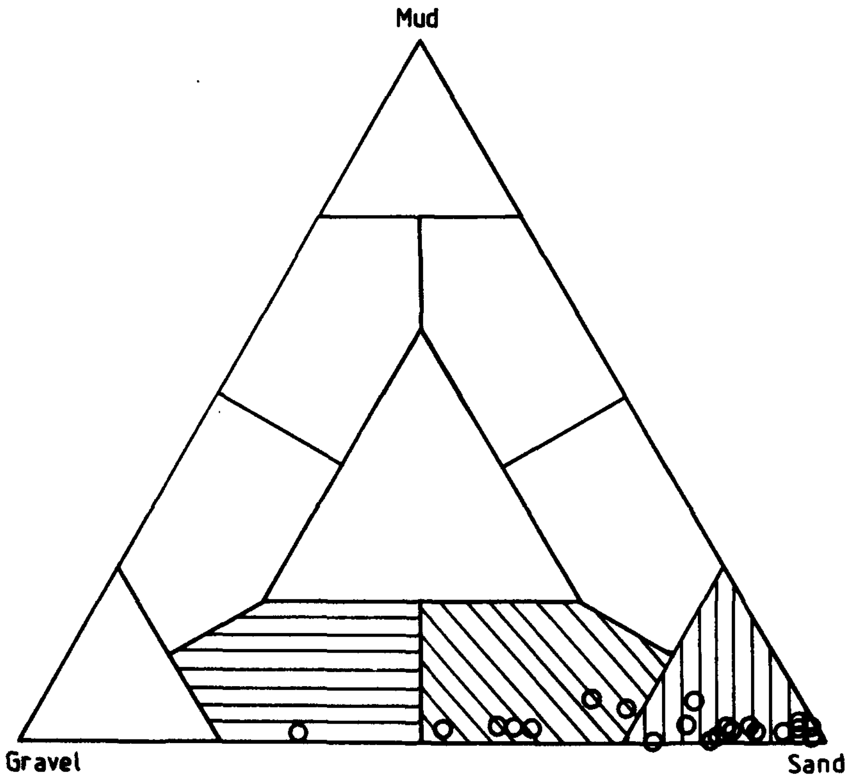

Figure 2: *Gravel/sand/mud triangle for Broome.*

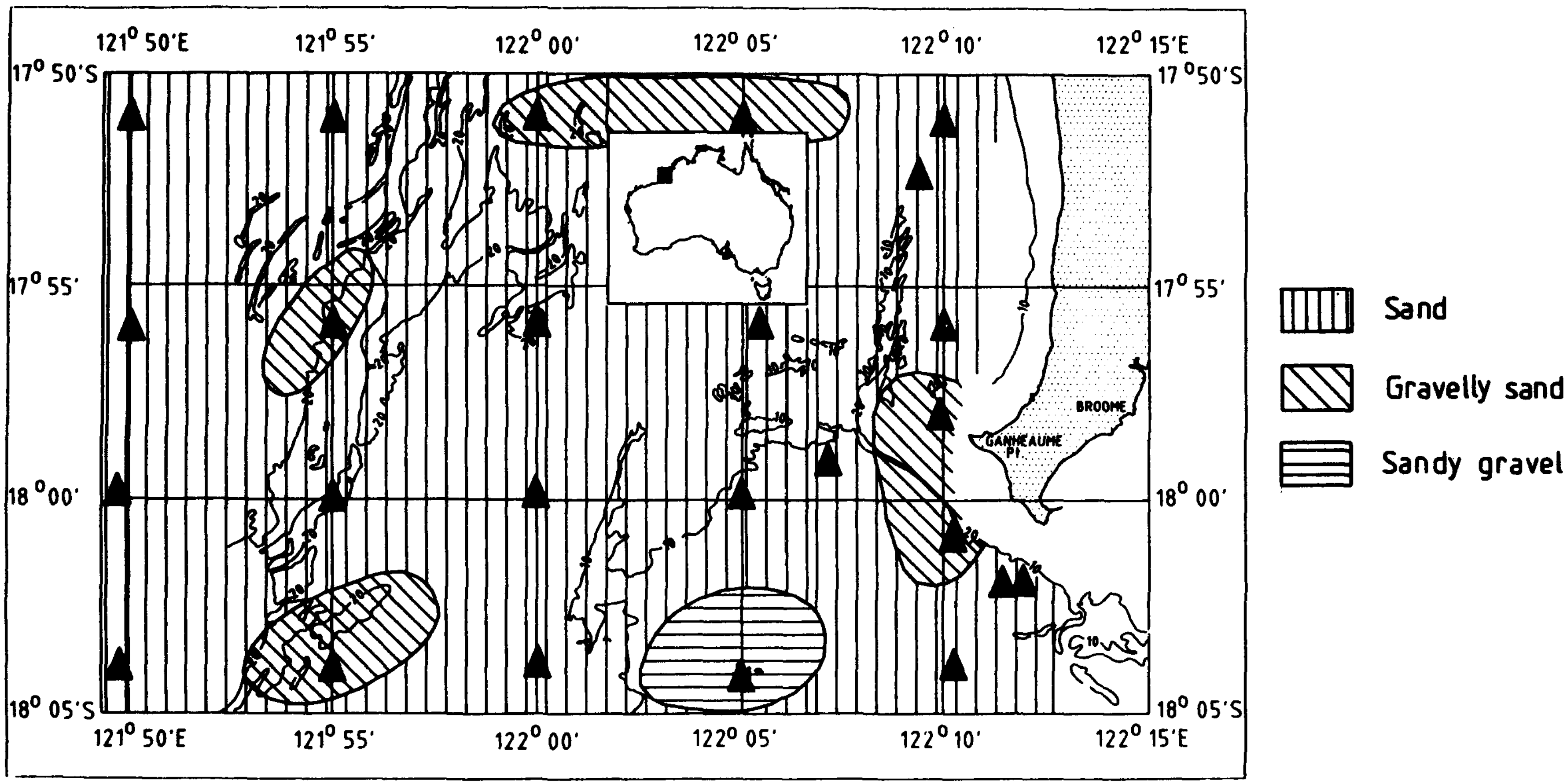

Figure 3: *Map of distribution of sediment types off Broome (▲ : station positions).*

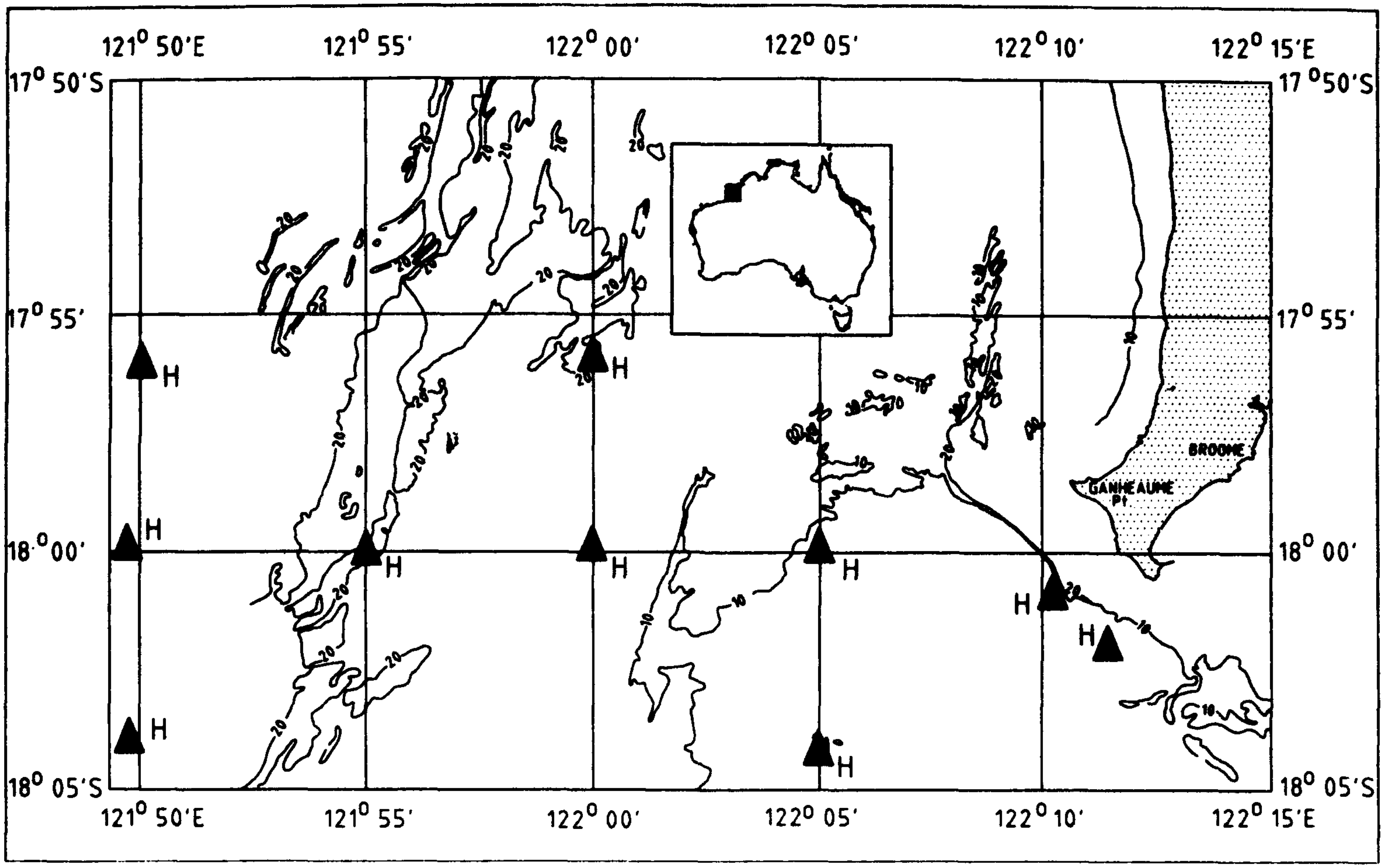

Figure 4: Positions where a hard bottom is suspected off Broome, marked with an H.

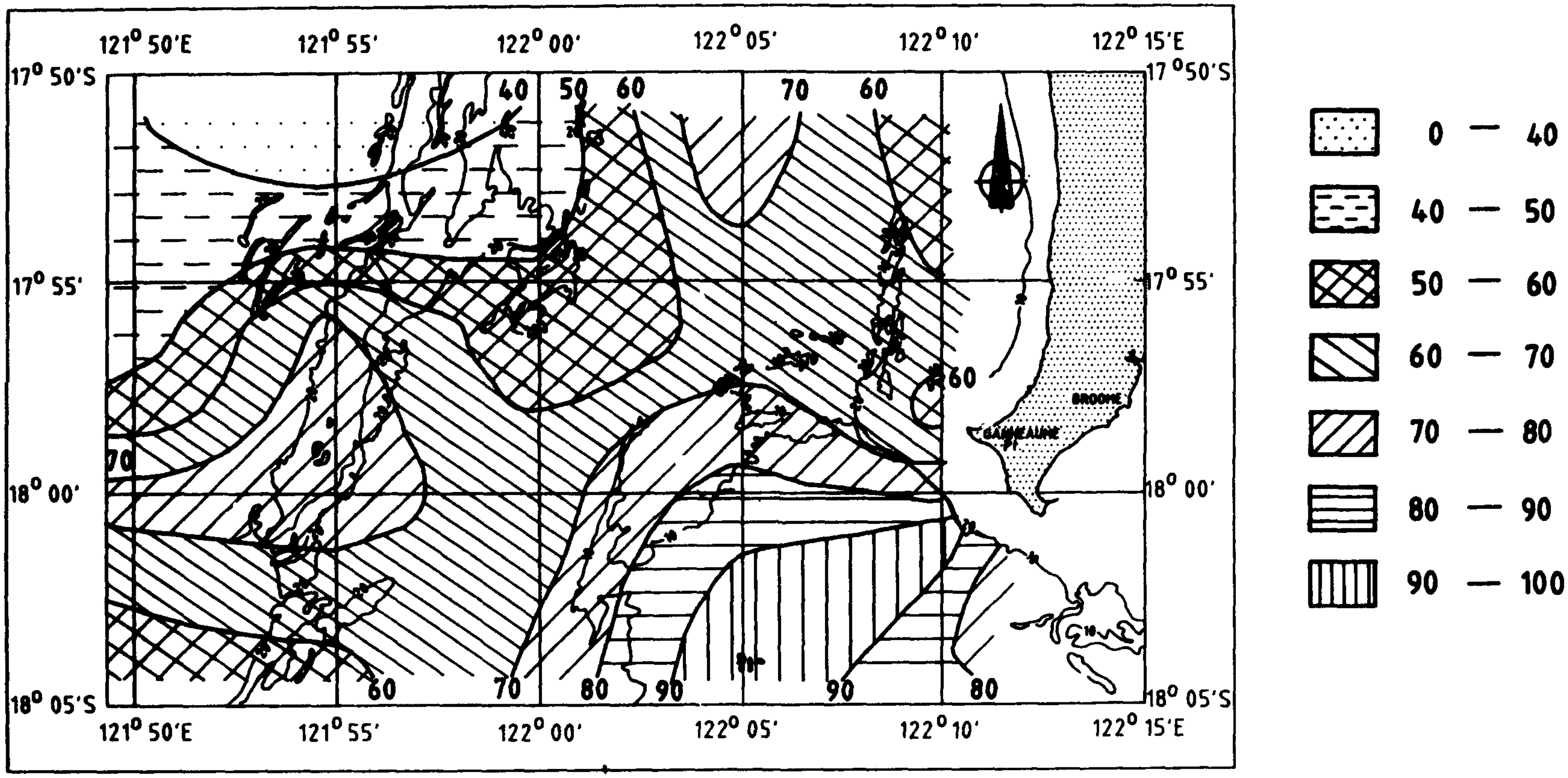

Figure 5: Map of distribution of carbonate percentage in whole samples off Broome.

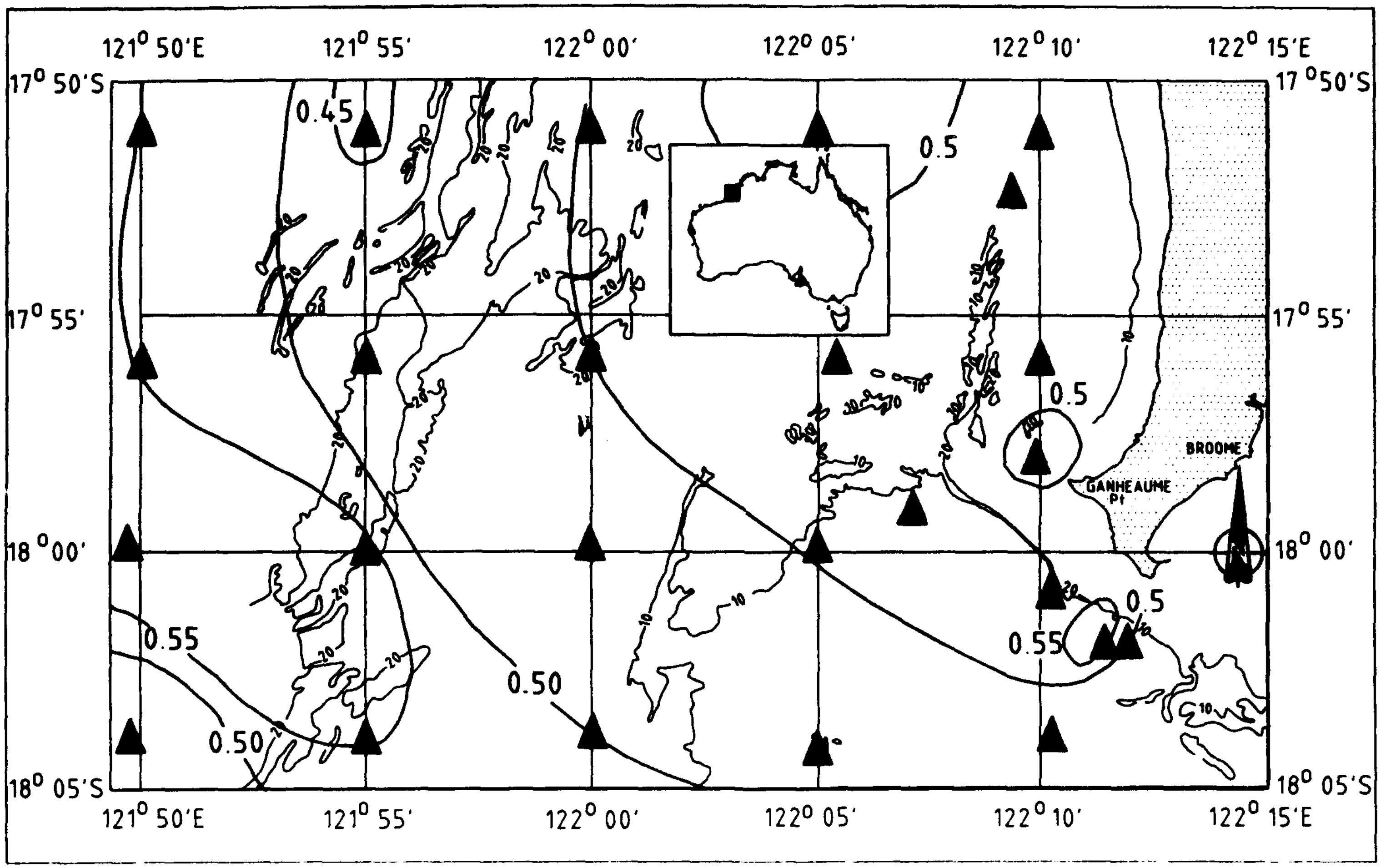

Figure 6: Map of distribution of porosity off Broome.

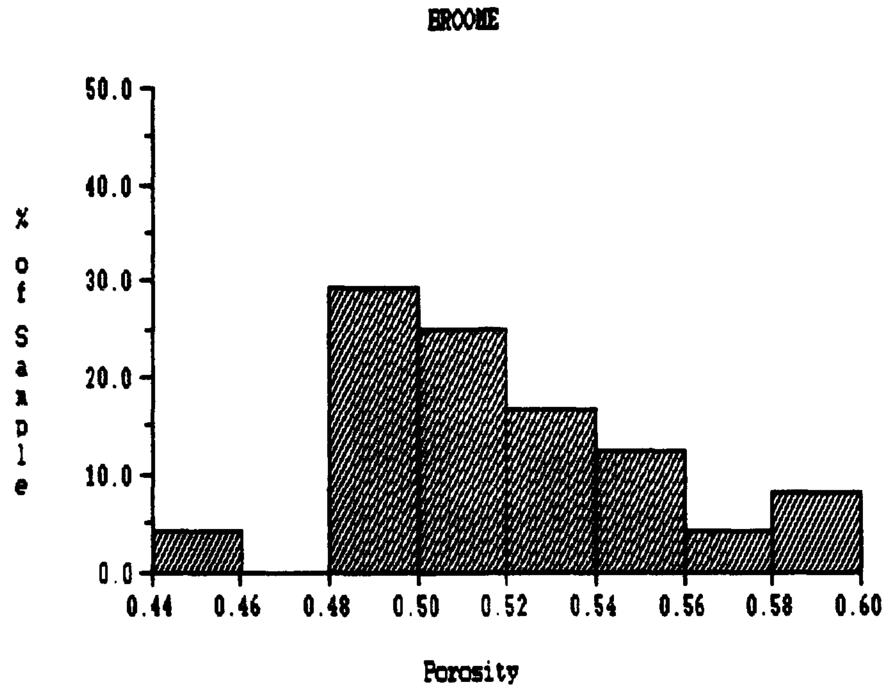

Figure 7: Histogram for porosity, off Broome.

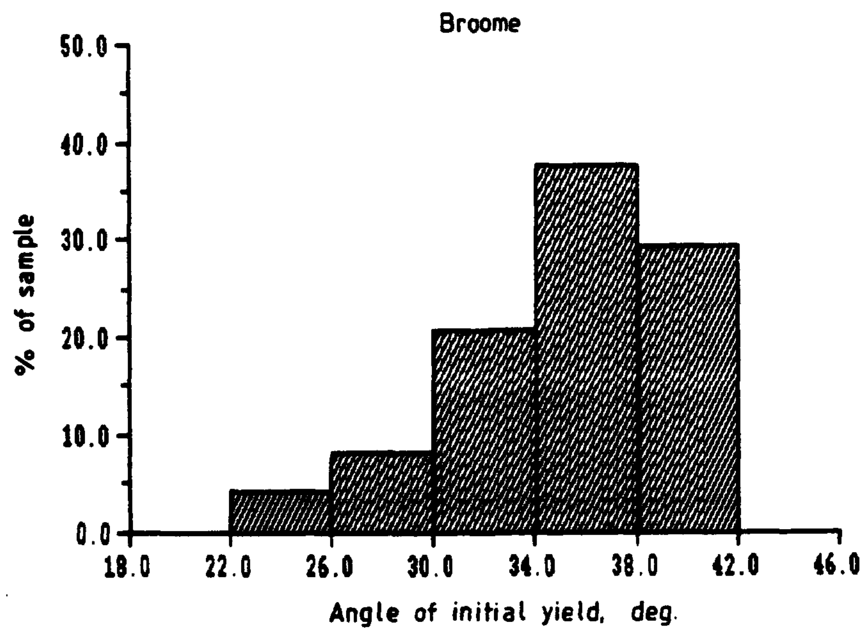

Figure 8: Histogram for angle of initial yield, off Broome.

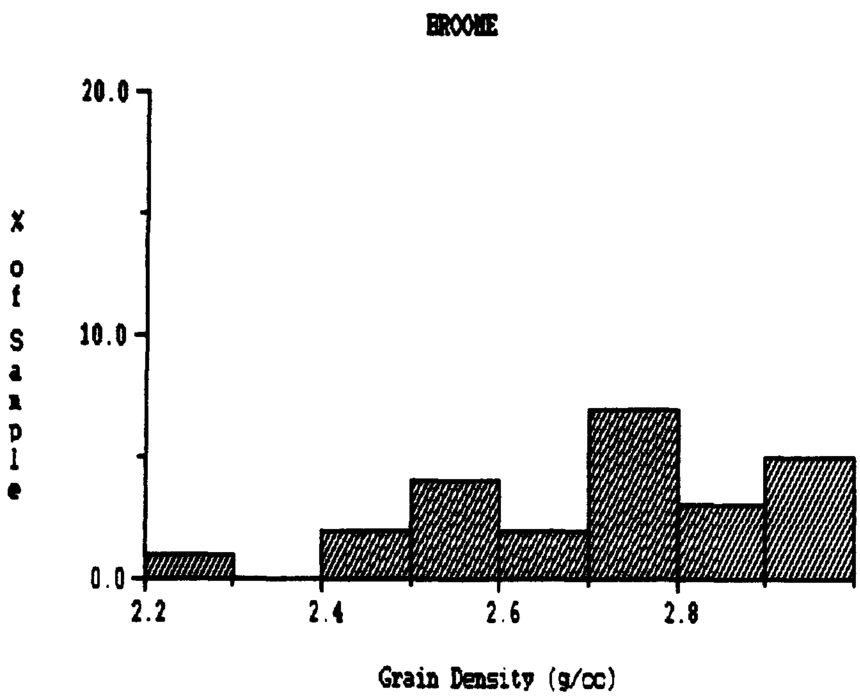

Figure 9: Histogram for sediment grain density, off Broome.

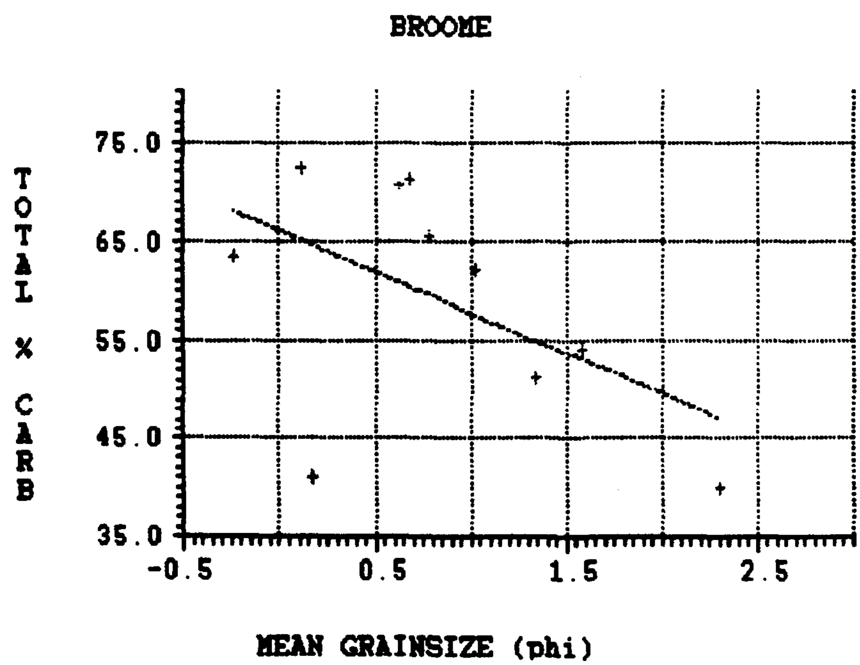

Figure 10: Regression between percentage carbonate in whole sample and M_Z, off Broome.

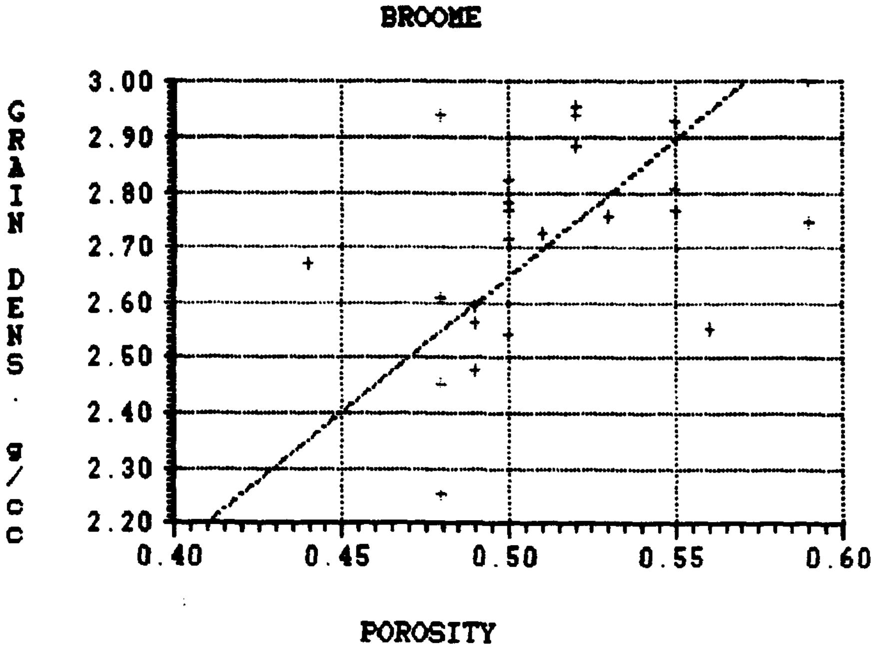

Figure 11: Regression between sediment grain density and porosity, off Broome.

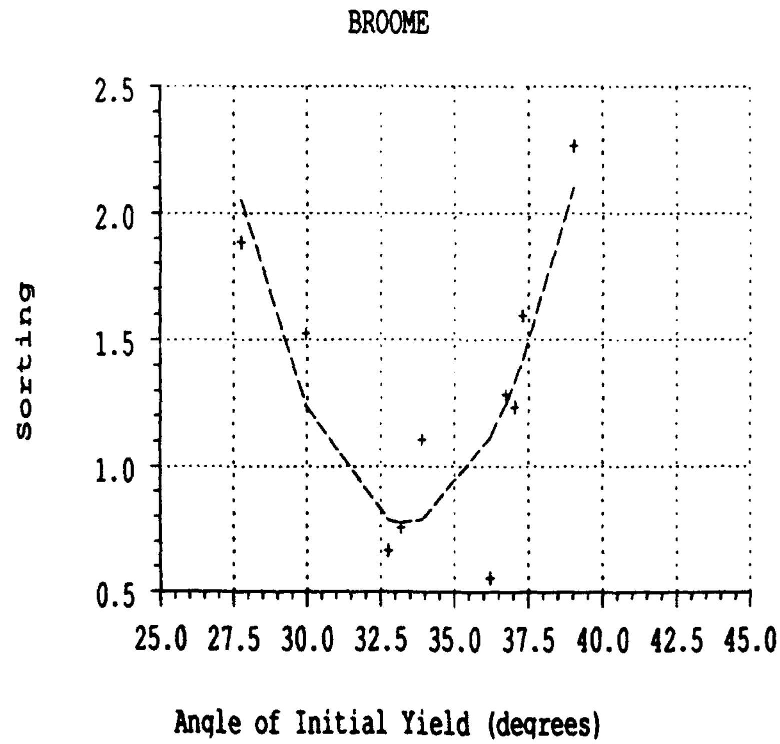

Figure 12: Regression between sorting, as measured by σ_1 and angle of initial yield, off Broome.

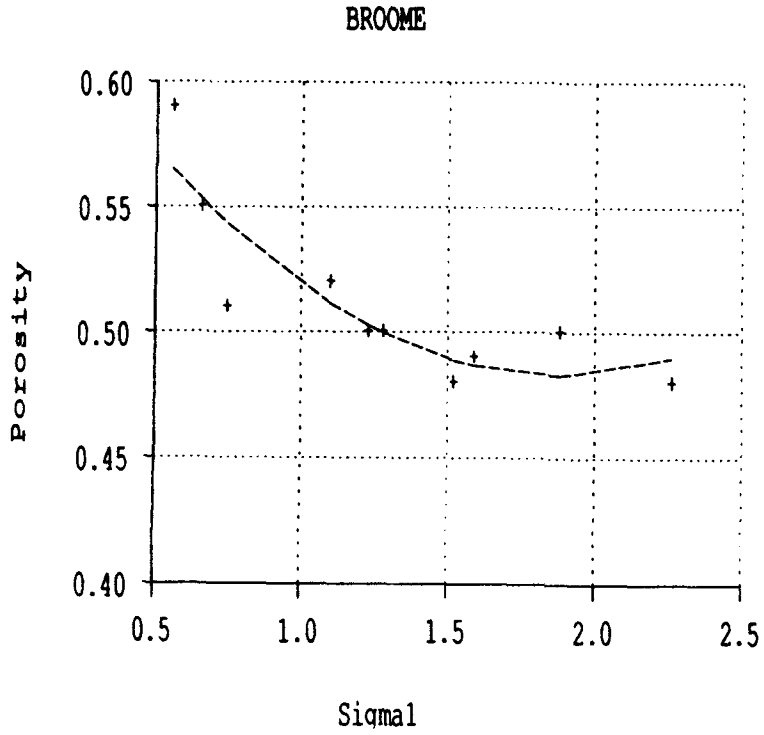

Figure 13: Regression between porosity and σ_1, off Broome.

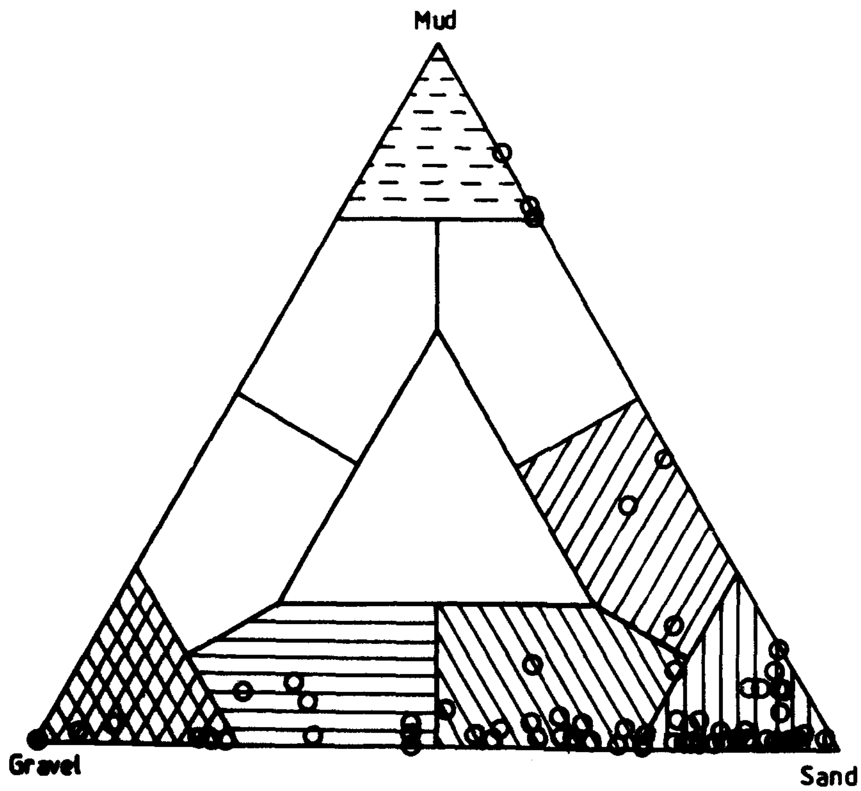

Figure 14: Gravel/sand/mud triangle for Port Hedland.

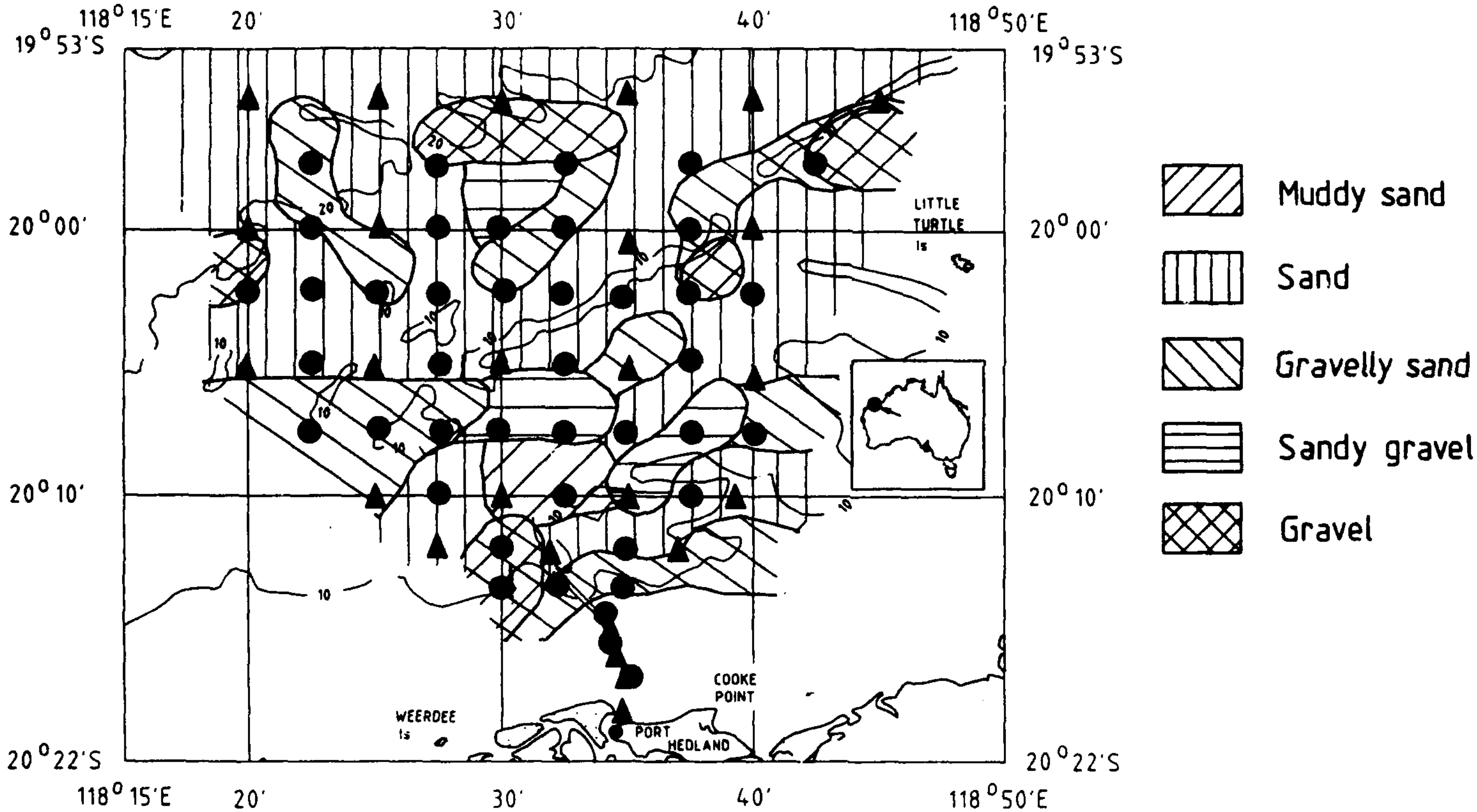

Figure 15: *Map of distribution of sediment types off Port Hedland. ▲, 1990 stations; ●, 1992 stations:*

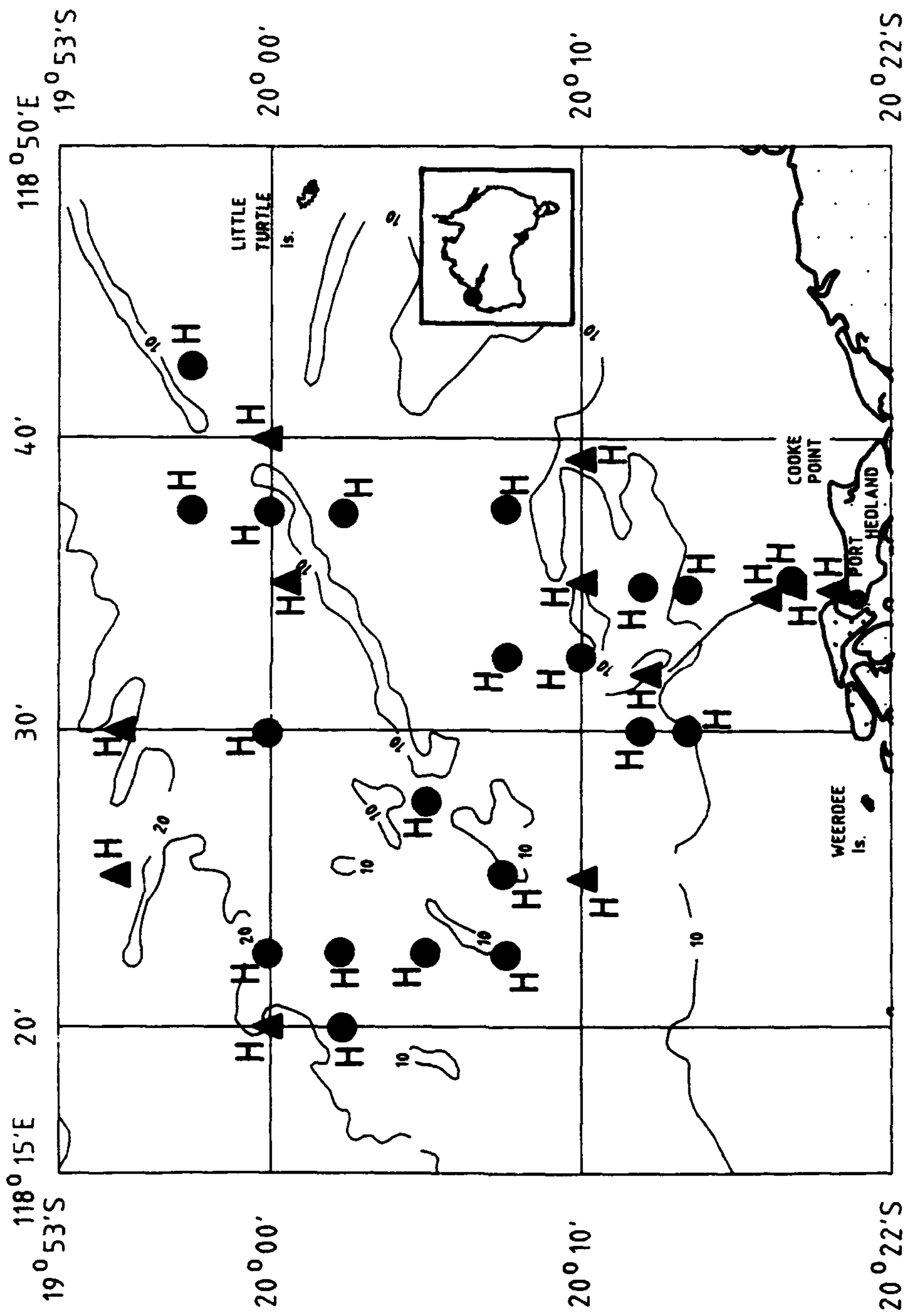

Figure 16: Positions where a hard bottom is suspected off Port Hedland, marked with an H.

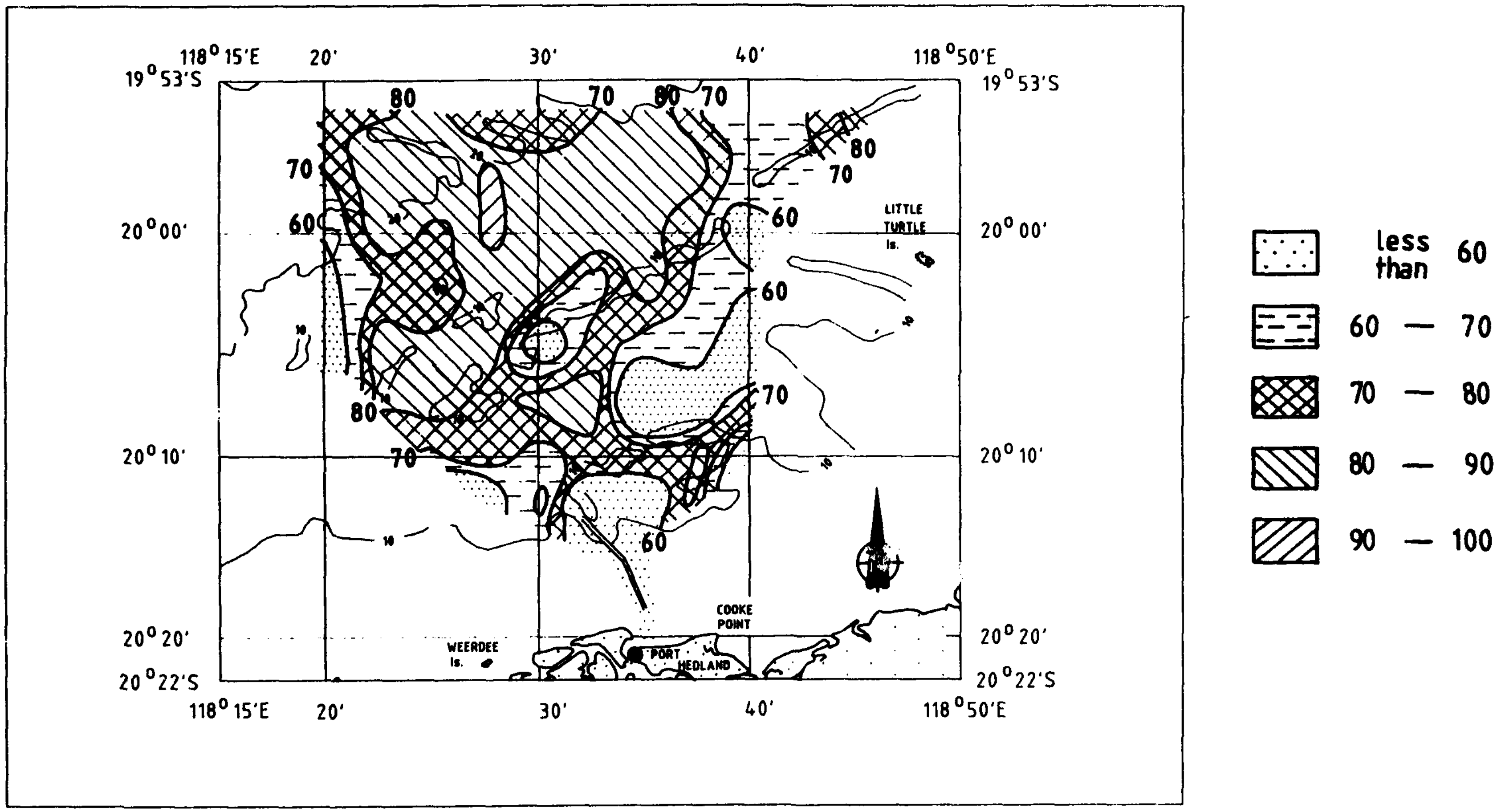

Figure 17: Map of distribution of carbonate percentage in sand fraction off Port Hedland.

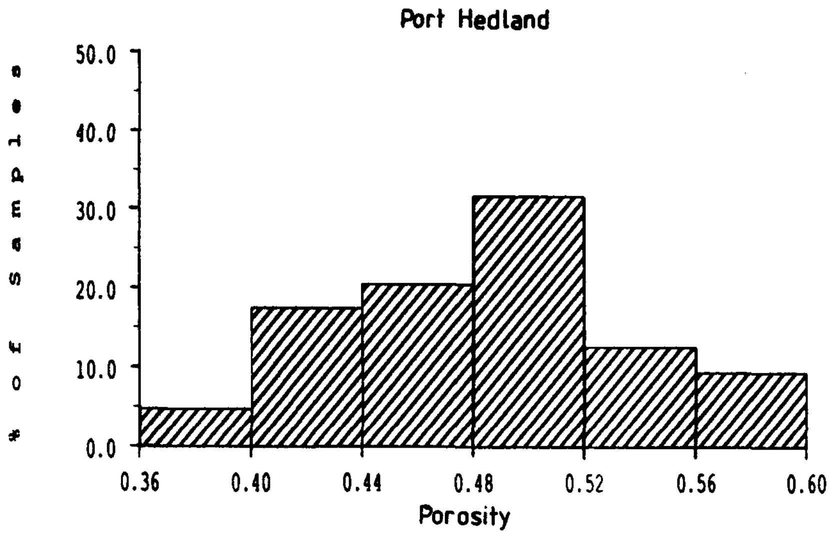

Figure 18: Histogram for porosity, off Port Hedland.

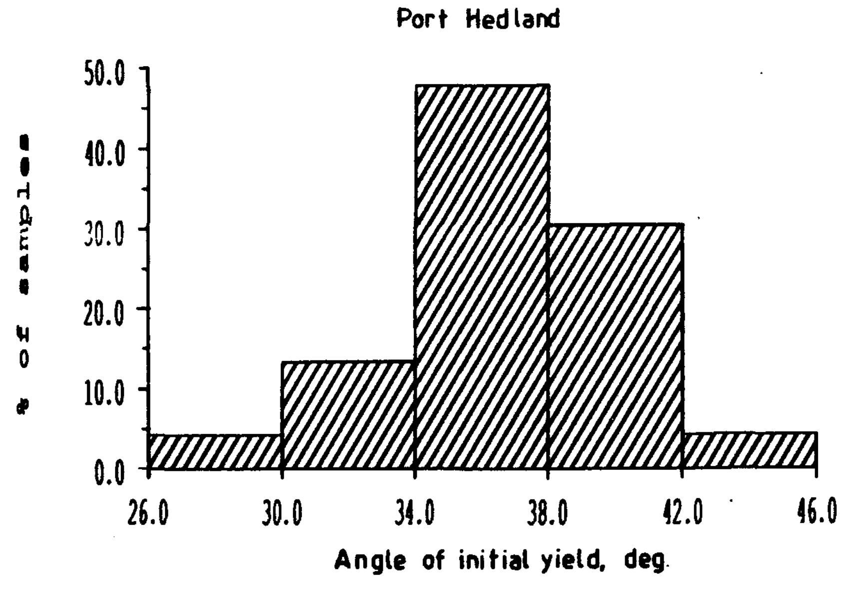

Figure 19: Histogram for angle of initial yield, off Port Hedland.

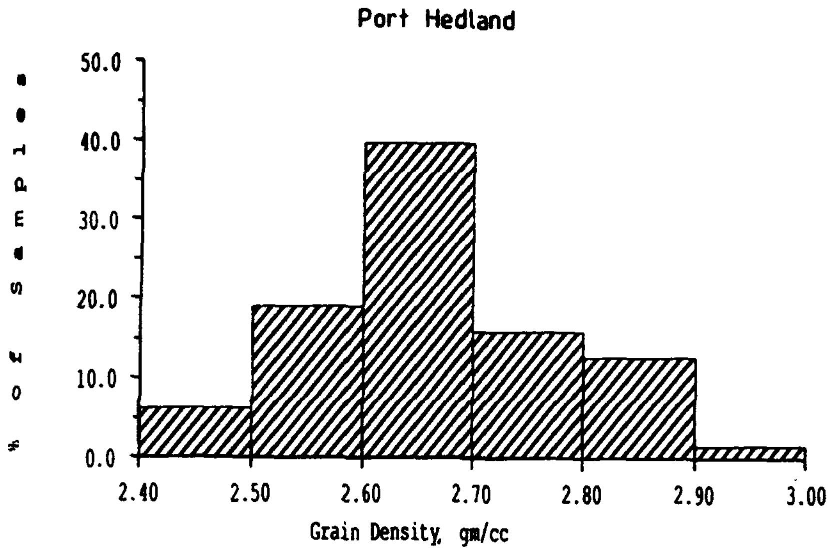

Figure 20: Histogram for sediment grain density, off Port Hedland.

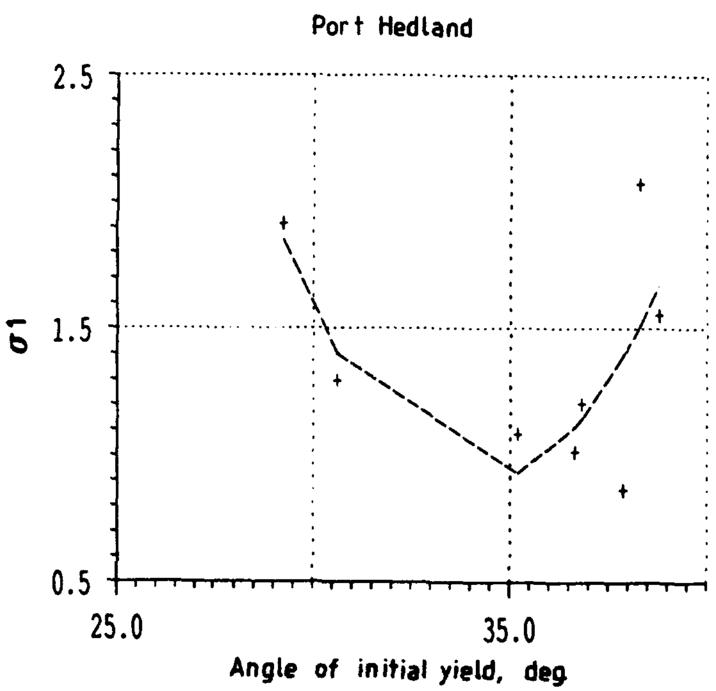

Figure 21: Regression between sorting, as measured by σ_1 and angle of initial yield, off Port Hedland.

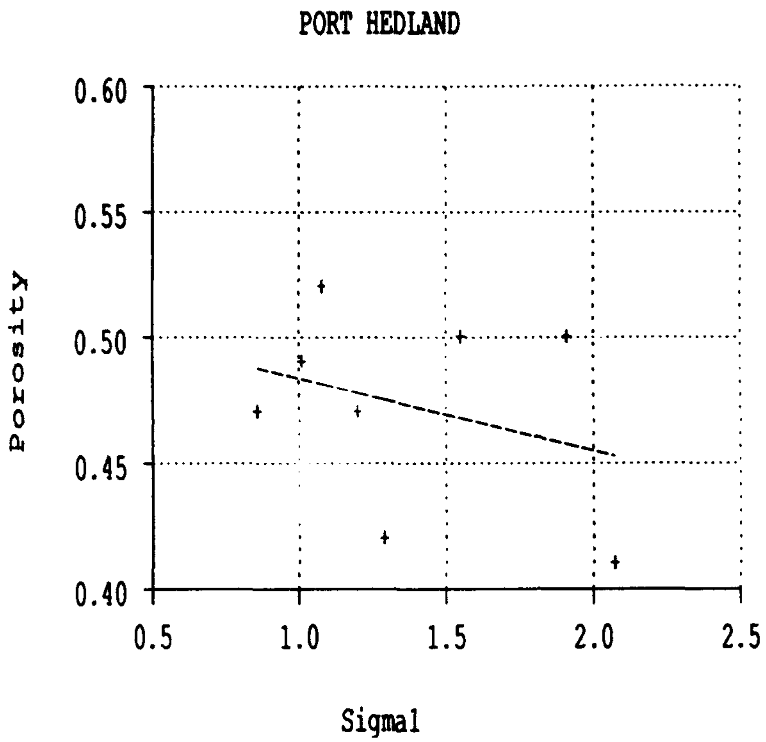

Figure 22: Regression between porosity and σ_1; off Port Hedland.

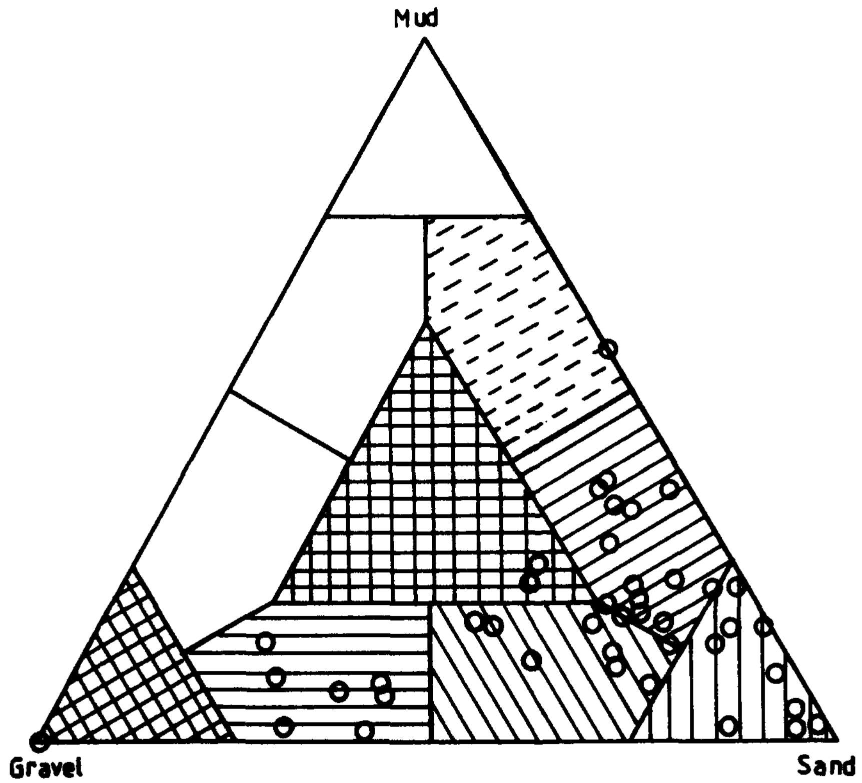

Figure 23: Gravel/sand/mud triangle for Darwin.

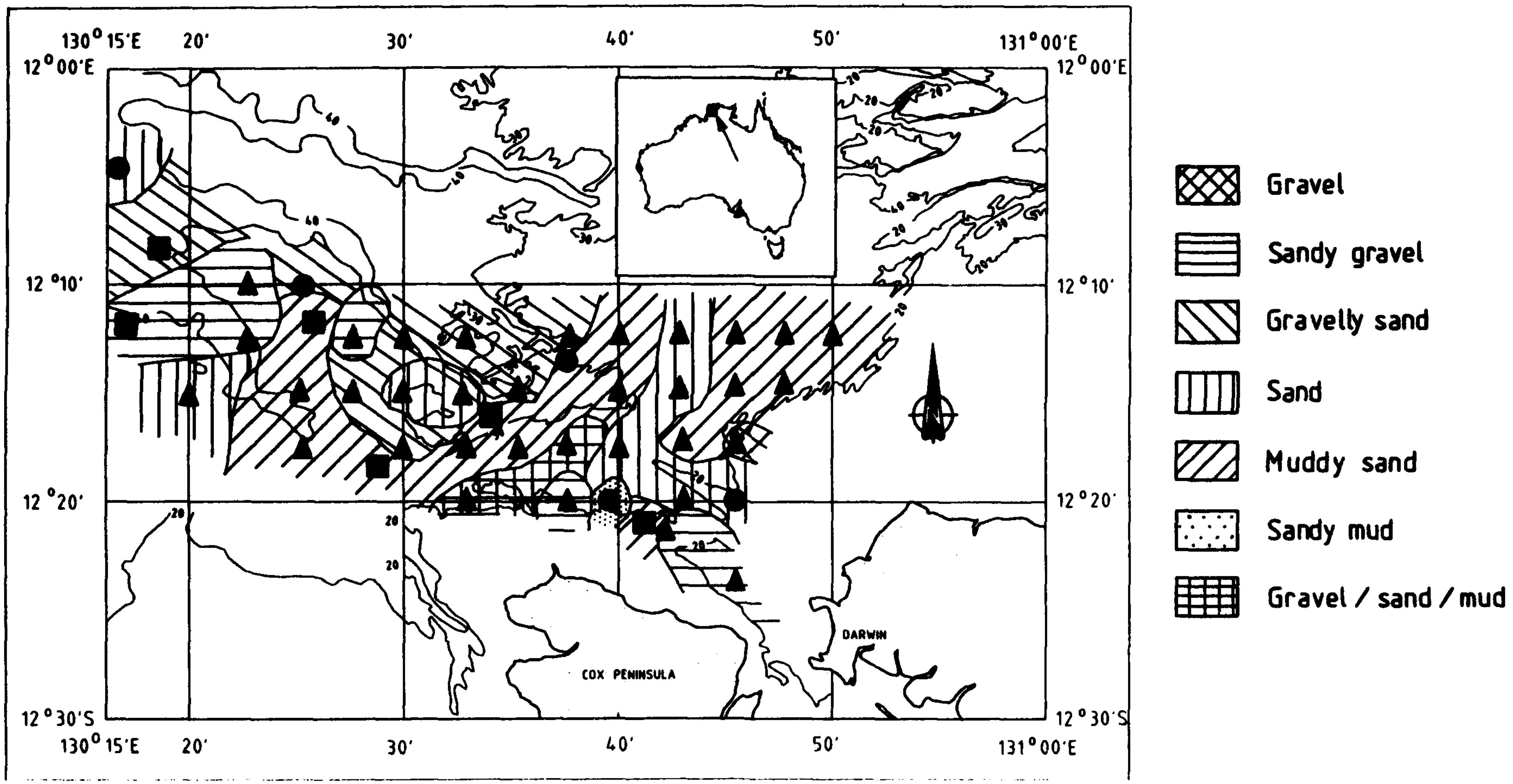

Figure 24: Map of distribution of sediment types off Darwin.

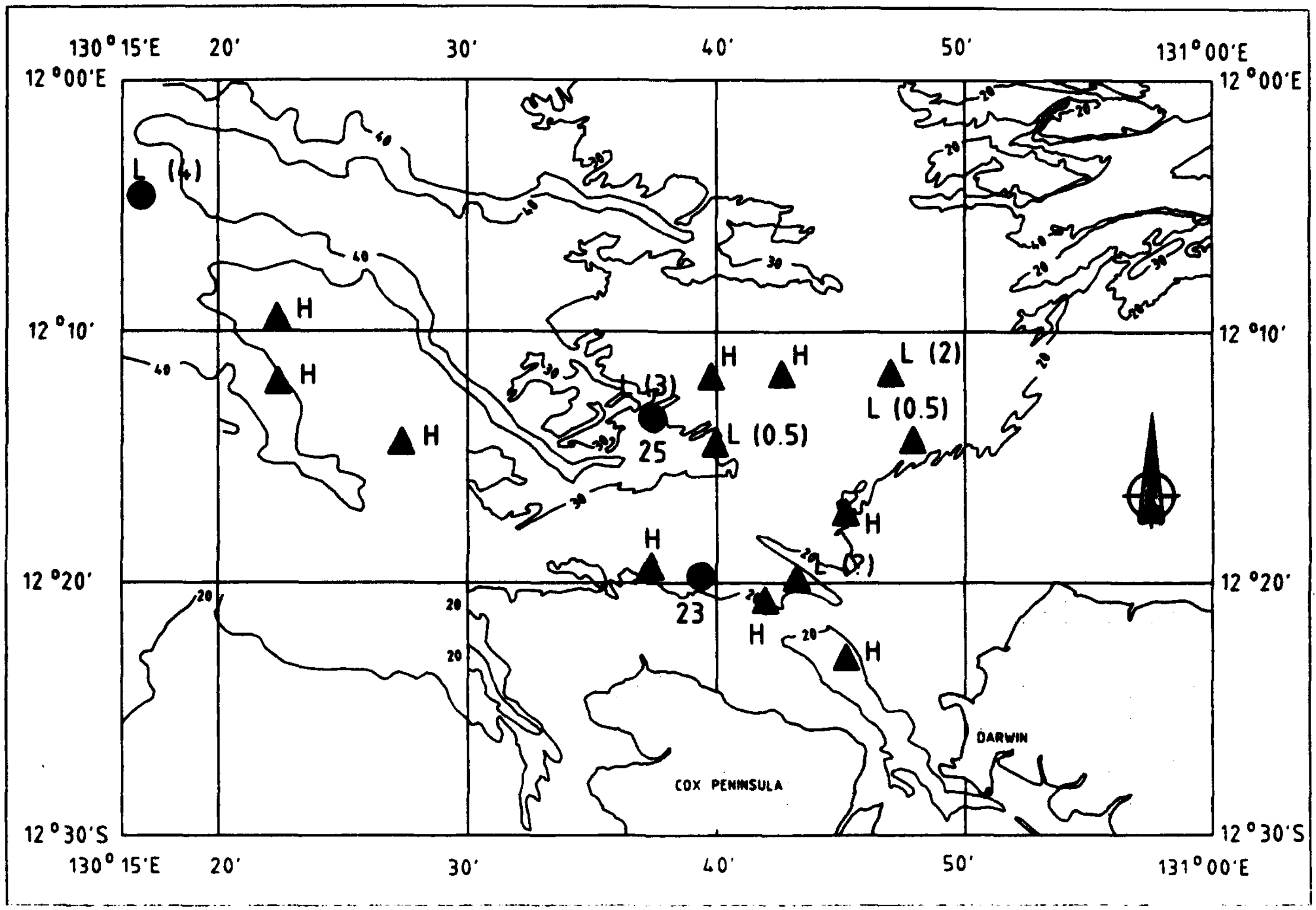

Figure 25: *Positions where a hard bottom is suspected off Darwin: ▲ H; positions 23 and 25, where sediment shear strength profiles were obtained: ●; positions where a thin, surface layer of yellowish muddy sand or sand was underlain by a green-grey layer with a higher mud content, with surface layer thickness, if known, in brackets (cm): ▲L, ●L.*

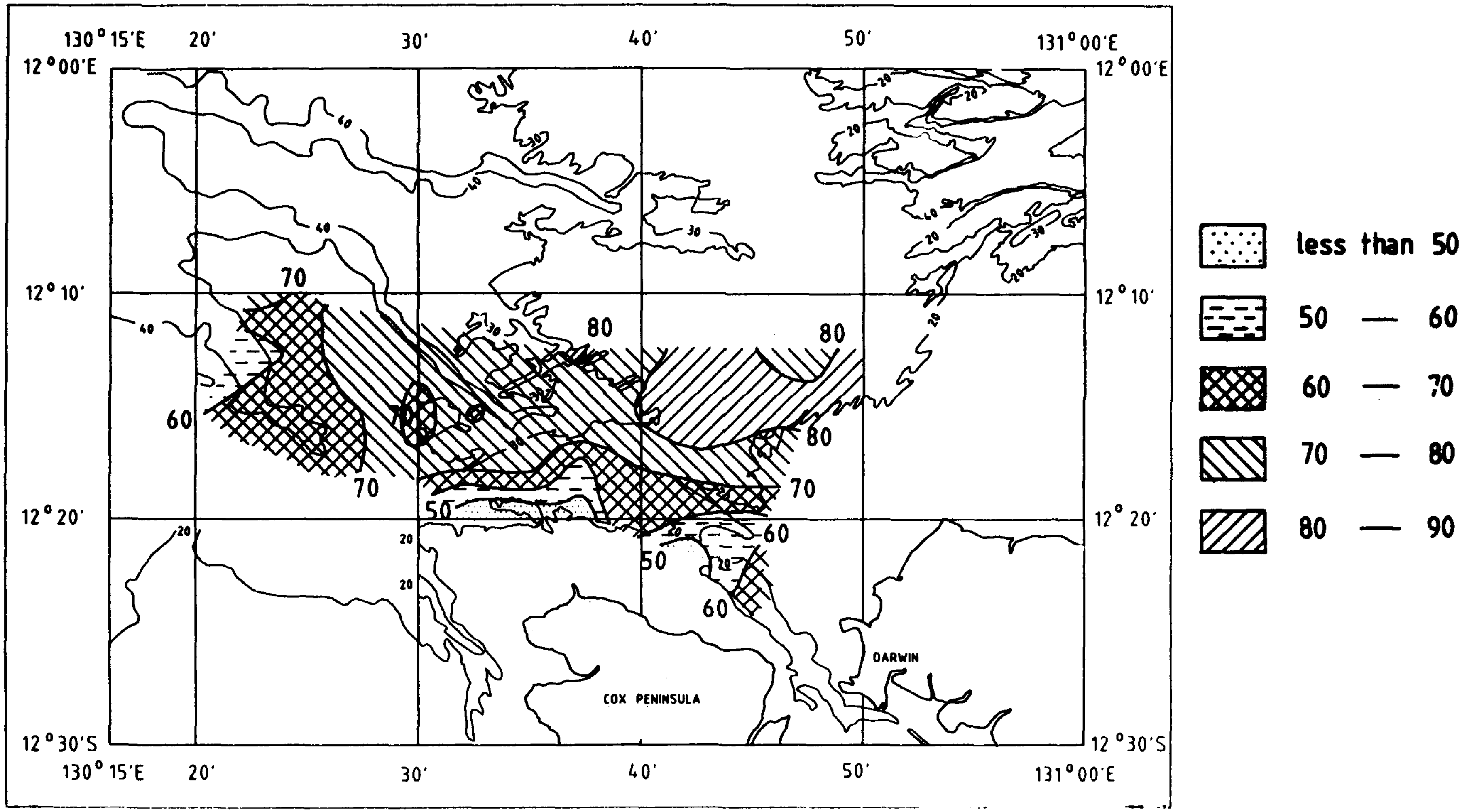

Figure 26: Map of distribution of carbonate percentage in sand fraction off Darwin (based on 1990 and 1992 data).

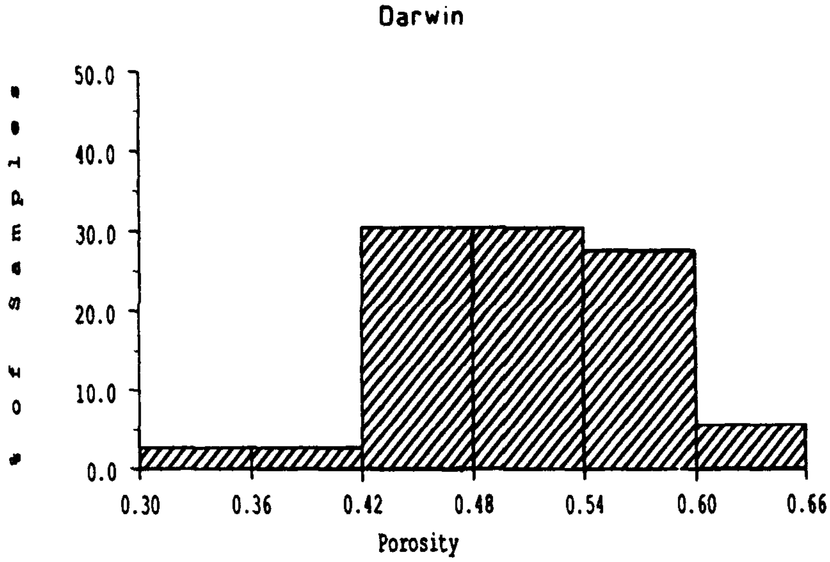

Figure 27: Histogram for porosity, off Darwin.

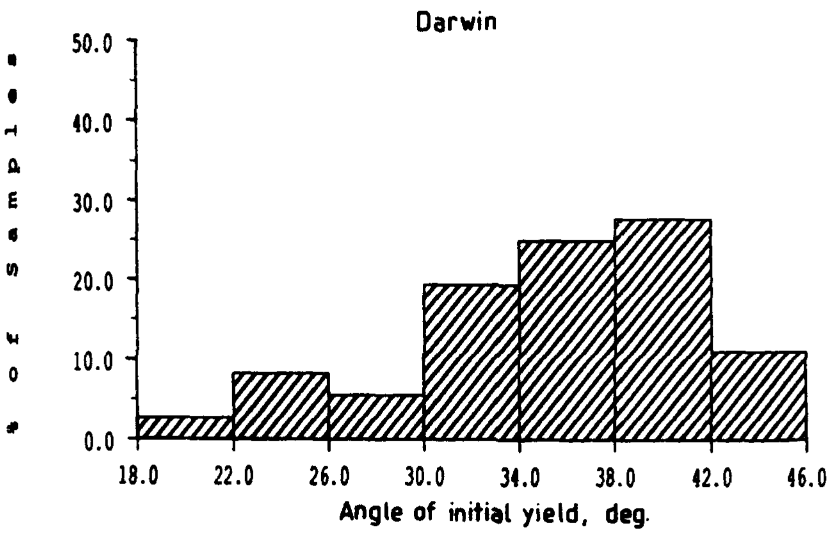

Figure 28: Histogram for angle of initial yield, off Darwin.

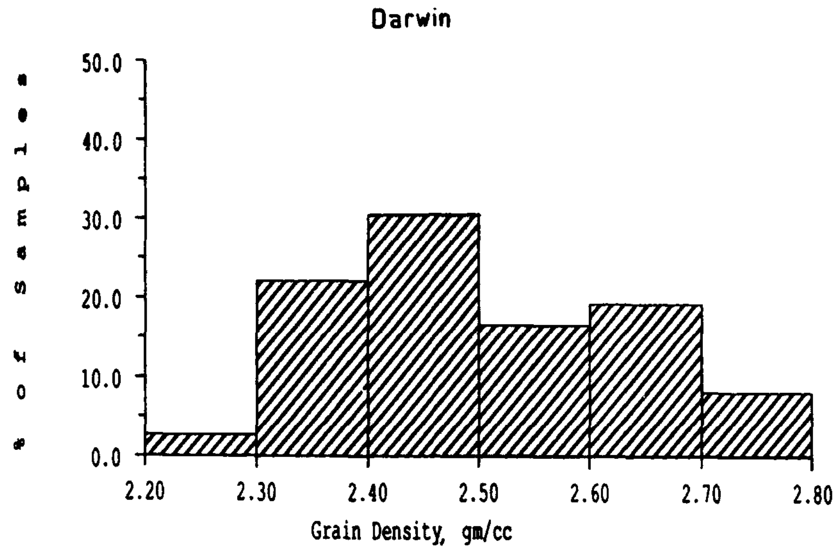

Figure 29: Histogram for sediment grain density, off Darwin.

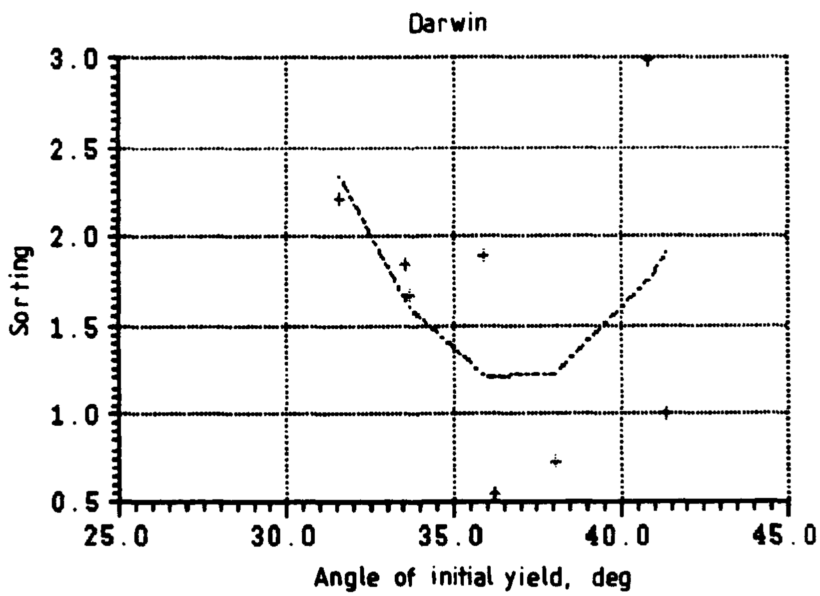

Figure 30: Regression between sorting, as measured by σ_1 and angle of initial yield, off Darwin.

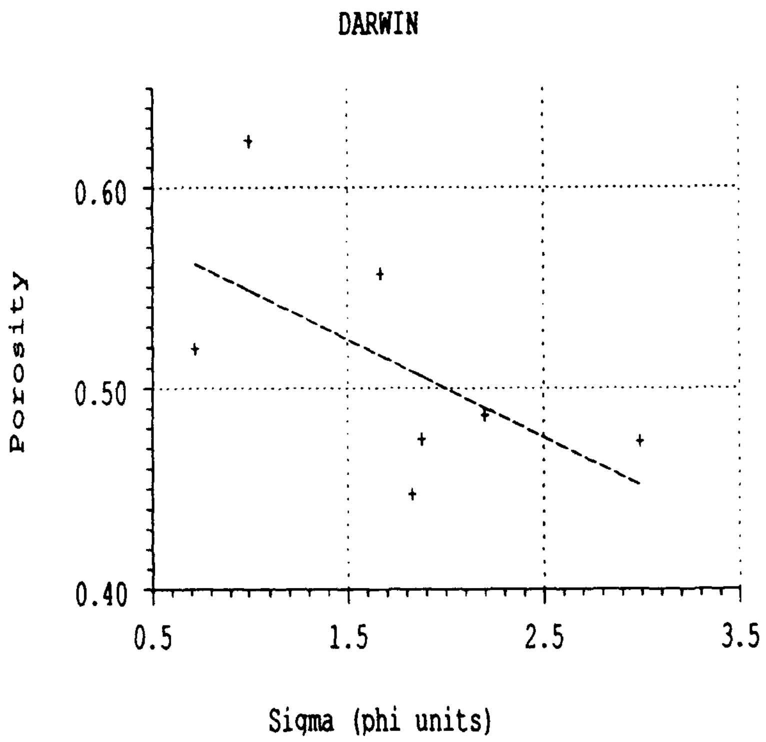

Figure 31: Regression between porosity and σ_1, off Darwin.

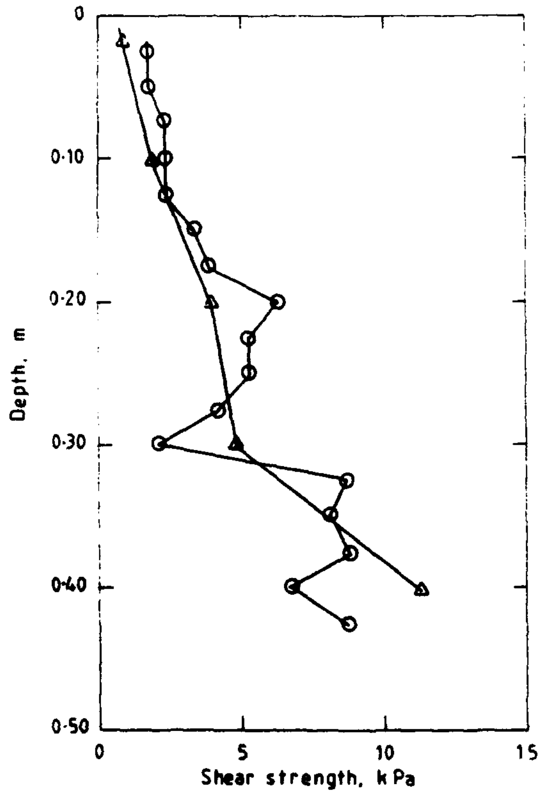

Figure 32: Sediment shear strength profiles off Darwin. o, Station 23; Δ, Station 25.

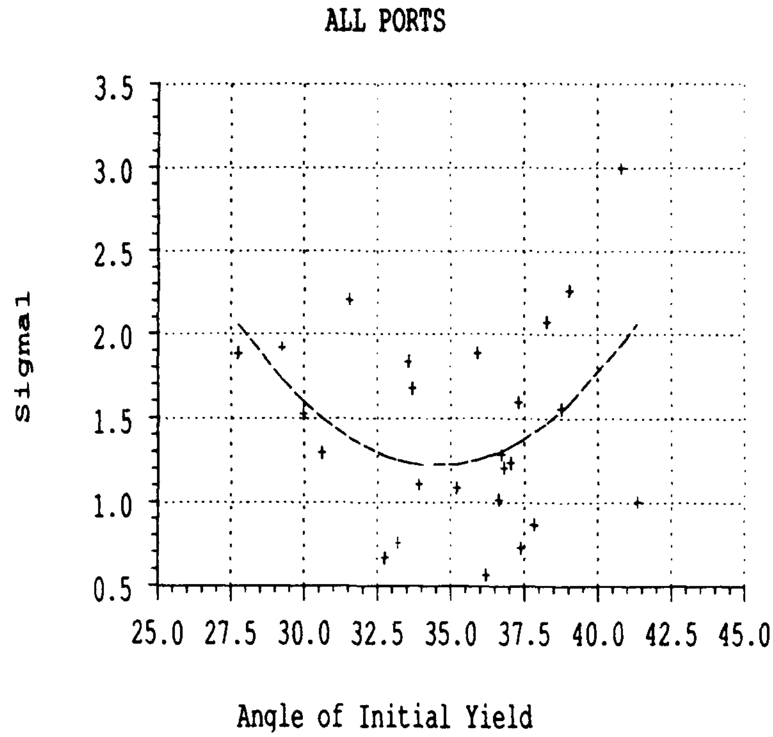

Figure 33: Regression between σ_1 and angle of initial yield, all three ports.

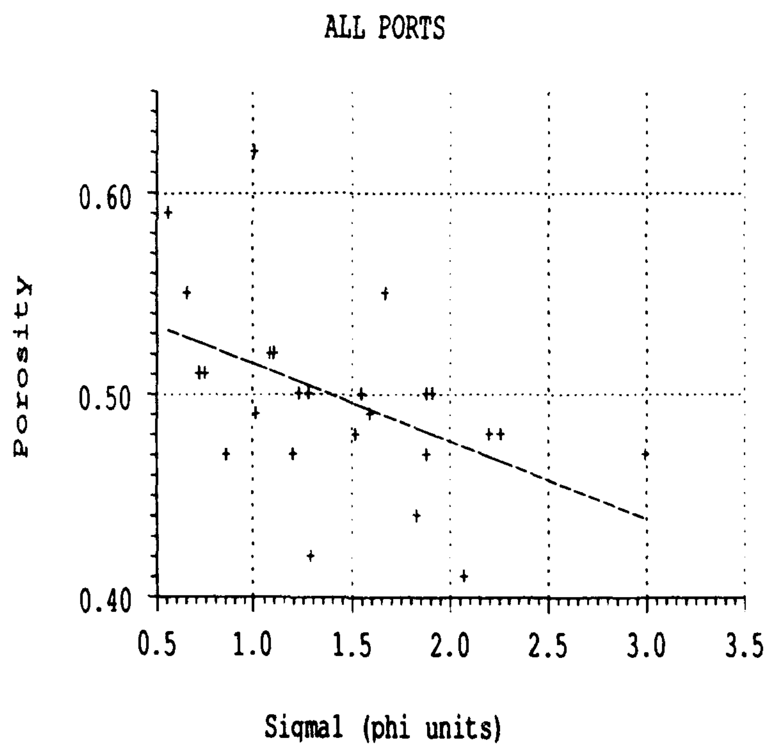

Figure 34: Regression between porosity and σ_1, all three ports.

APPENDIX A

Station Locations and Sediment Properties

Station	Latitude	Longitude	Water Depth(m)	%gravel	%sand	%mud	% Carbonate Sand	Mud	Total	
Stations off Broome, HMAS Bunbury Dec.90:										
2	18 02.0	122 11.9	13	2.2	97.3	tr	70.4	6.4	70.7	
3	18 02.0	122 11.4	13	0.5	99.4	tr	70.3	42.3	70.4	
4	18 01.1	122 10.1	13	37.4	61.8	0.8	86.9	62.8	91.6	
7	17 58.0	122 09.9	24	21.5	73.5	5.0	43.7	65.8	56.9	
8	17 56.0	122 10.0	16	13.0	86.8	tr	58.1	40.2	63.5	
9	17 55.9	122 05.1	16	2.6	96.6	0.8	60.9	51.2	61.8	
10	17 56.0	122 00.0	21	4.4	94.6	1.0	51.9	39.4	53.9	
11	17 56.0	121 55.0	20	25.7	68.7	5.6	63.0	57.9	72.4	
12	17 56.0	121 49.9	37	tr	98.6	1.0	39.5	52.4	39.9	
13	17 51.0	121 50.0	35	2.1	96.3	1.6	40.8	59.0	42.3	
14	17 51.0	121 55.0	25	1.4	98.0	0.6	26.1	60.2	27.3	
15	17 51.0	122 00.1	17	35.5	62.8	1.7	7.0	70.9	41.1	
16	17 51.0	122 05.0	18	38.5	59.8	1.7	65.9	70.8	79.1	
17	17 51.0	122 09.9	15	12.5	87.2	tr	43.7	65.8	50.8	
18	18 00.0	121 49.7	35	0.7	98.1	1.2	73.8	58.4	73.1	
19	18 00.0	121 55.0	20	7.6	91.8	0.7	72.6	55.4	74.6	
20	18 00.0	122 00.0	20	17.1	85.1	1.2	55.7	70.7	65.3	
21	18 00.1	122 05.0	13	10.0	88.7	1.3	83.9	94.2	85.6	
22	17 59.2	122 07.0	12	20.5	79.3	tr	67.2	41.8	73.9	
23	18 04.1	122 10.1	13	12.6	80.3	7.1	79.2	76.6	81.6	
24	18 04.6	122 05.0	13	65.4	34.1	0.4	92.0	52.8	98.9	
25	18 04.0	122 00.0	15	11.4	86.9	1.7	67.2	71.7	71.0	
26	18 04.0	121 55.0	12	46.3	52.2	1.5	23.5	71.2	59.6	
27	18 04.0	121 49.7	30	7.9	90.2	2.2	46.1	71.1	51.0	
Stations off Port Hedland, HMAS Dubbo Feb. 1992:										
1	20 17.4	118 35.3	15	0.0	23.7	76.3	15.1	23.3		
2	20 16.7	118 35.0	15	71.4	21.6	7.0	12.3	12.6		
3	20 15.5	118 34.4	15	0.0	15.4	84.6	14.7	22.4		
4	20 14.5	118 33.9	16	0.3	23.6	76.1	10.9	23.5		
5	20 13.5	118 30.0	13	100.0	0.0	0.0	76.7	*	92.2	92.2
6	20 13.5	118 32.5	16	32.2	55.9	11.9	13.0	45.7	52.1	29.5
7	20 13.5	118 35.0	15	44.9	54.3	0.7	64.5	20.0	83.8	72.8
8	20 12.0	118 30.0	16	76.0	23.7	0.2	82.8	26.3	84.2	83.7
9	20 12.0	118 35.0	17	16.4	83.4	1.2	14.8	14.2	59.9	22.3
10	20 10.0	118 27.5	19	18.2	78.6	3.2	77.9	40.1	89.4	78.8
11	20 10.0	118 32.5	21	11.8	71.0	17.2	78.4	44.1	94.6	74.4

Station	Latitude	Longitude	Water Depth(m)	%gravel	%sand	%mud	% Carbonate Sand	Mud	Gravel	Total
12	20 10.0	118 37.5	11	13.9	84.4	1.8	80.5	42.2	97.7	82.3
13	20 07.5	118 22.5	22	32.5	67.0	0.6	80.8	32.0	91.8	84.2
14	20 07.5	118 25.0	20	37.1	62.6	0.4	86.4	37.4	98.1	90.6
15	20 07.5	118 27.5	16	37.3	60.8	1.9	75.1	46.8		
16	20 07.5	118 30.0	19	64.5	30.7	4.8	84.6	37.4		
17	20 07.5	118 32.5	20	52.3	46.8	0.9	83.5	14.5	86.3	84.3
18	20 07.5	118 35.0	20	2.5	89.8	7.7	27.7	42.5	92.1	30.4
19	20 07.5	118 37.5	18	64.6	26.8	8.7	43.3	34.5		
20	20 07.5	118 40.0	16	33.7	65.5	0.8	76.7	38.7	86.6	80.0
21	20 05.0	118 22.5	20	11.5	88.2	0.3	87.9	35.9	92.1	88.2
22	20 05.0	118 27.5	19	5.9	93.8	0.3	86.3	35.1	99.8	87.1
23	20 05.5	118 32.5	18	11.1	87.2	1.8	76.2	48.5	85.7	76.8
24	20 05.0	118 37.5	17	20.0	79.8	0.1	69.3	40.3	84.9	72.3
25	20 02.5	118 20.0	26	89.8	8.5	1.7	*	*		
26	20 02.5	118 22.5	15	18.0	81.8	0.3	69.7	59.6	96.6	74.6
27	20 02.5	118 25.0	22	42.5	57.0	0.5	71.3	39.6		
28	20 02.5	118 27.5	22	5.3	94.6	0.1	88.1	69.6	93.6	88.4
29	20 02.5	118 30.5	23	41.9	56.8	1.3	80.8	48.8		
30	20 02.5	118 32.5	21	5.0	93.5	1.5	62.7	47.3	96.7	64.2
31	20 02.5	118 35.0	20	23.2	75.7	1.1	88.0	47.3	94.1	89.0
32	20 02.5	118 37.5	18	94.8	4.8	0.4	65.8			
33	20 02.5	118 40.0	20	0.2	84.5	13.5	63.7	48.6	88.3	60.6
34	20 00.0	118 22.5	25	30.0	69.1	0.5	89.8	24.9		
35	20 00.0	118 27.5	22	16.6	79.6	3.9	92.6	39.9	88.6	90.0
36	20 00.0	118 30.0	22	52.8	46.6	0.6	81.6	29.7		
37	20 00.0	118 32.5	22	31.0	67.0	1.9	88.6	46.4	87.3	87.3
38	20 00.0	118 37.5	21	24.5	72.0	3.5	69.7	37.9	97.9	75.5
39	19 57.5	118 22.5	32	65.1	34.3	0.6	86.9	28.7	97.0	93.1
40	19 57.5	118 27.5	25	77.6	22.3	0.2	91.2	27.5	94.2	93.5
41	19 57.5	118 32.5	22	79.9	19.9	0.1	88.6		91.8	91.0
42	19 57.5	118 37.5	18	19.6	80.4	0.0	84.8			
43	19 57.5	118 42.5	16	100.0	0.0	0.0			93.0	93.0
Stations off Port Hedland, HMAS Geraldton Dec 1990:										
37	20 17.9	118 34.9	19	5.9	86.4	7.7	3.2	12.5	20.8	5.0
38	20 16.9	118 35.2	19	15.4	75.0	9.6	6.7	17.1		
39	20 15.9	118 34.7	19	tr	85.5	14.5	8.2	17.7		9.6
40	20 15.2	118 34.4	19	0.8	58.0	41.2	30.8	24.1		
41	20 12.0	118 32.0	14	5.5	90.9	3.6	40.5	30.5	87.9	42.7
42	20 12.0	118 27.6	17	5.9	93.5	0.6	40.6	23.4		
43	20 12.0	118 37.0	14	32.4	63.9	3.7	80.6	32.8		
44	20 09.9	118 25.0	20	26.8	72.9	tr	68.3	38.4	84.4	72.4
45	20 09.9	118 30.0	20	8.2	56.8	35.0	63.1	30.3		
46	20 09.9	118 35.0	13	53.3	46.3	tr	74.6	34.7	87.9	81.4
47	20 10.01	118 40.04	13	2.0	86.9	11.1	38.4	2.3	86.6	35.3
48	20 05.34	118 40.0	20	2.0	88.8	9.2	32.3	22.2		
49	20 05.0	118 35.36	18	46.9	48.5	4.6	62.2	49.2		

Station	Latitude	Longitude	Water Depth(m)	%gravel	%sand	%mud	% Carbonate Sand	Mud	Gravel	Total
50	20 04.9	118 30.04	18	5.3	87.8	6.9	47.3	50.8	90.6	49.8
51	20 05.0	118 24.8	19	13.5	85.7	0.8	83.1	29.7	88.7	83.4
52	20 05.0	118 20.0	20	14.6	85.2	tr	42.6	21.1		
53	20.00.0	118 20.0	24	8.7	90.7	0.6	61.7	41.2		
54	20 00.0	118 25.1	20	7.3	91.9	0.7	75.8	42.7	89.9	76.5
56	20 00.6	118 35.07	18	12.8	86.8	tr	82.4	32.9		
57	19 59.8	118 40.0	19	23.6	76.0	tr	44.8	38.1		
58	19 54.9	118 45.03	18	19.3	79.5	1.2	84.7	36.4		
59	19 55.0	118 40.0	21	14.2	85.0	0.8	53.3	43.9		
60	19 55.0	118 35.07	20	16.0	81.5	2.5	87.6	56.6		
61	19 55.0	118 29.96	25	3.9	94.6	1.5	70.9	12.9		
62	19 55.0	118 25.0	25	tr	99.3	0.6	81.2	4[illegible].9		
63	19 55.0	118 20.0	25	5.4	93.5	1.1	78.3	63.8	84.7	78.5

Stations off Darwin, LCM-8, Feb. 1992:

46	12 24.0	130 45.0	18	69.4	29.5	3.6	68.3	28.9	53.9	58.6
48	12 21.0	130 42.0	9	40.2	58.6	1.2	38.9	28.7	70.1	76.8
50	12 20.0	130 42.5	18	2.2	75.9	21.9	56.8	25.3		
51	12 20.0	130 37.5	15	63.7	21.4	14.9	42.0	28.1	24.1	28.5
52	12 20.0	130 32.5	20	23.0	49.4	27.5	41.3	24.1		
55	12 17.5	130 45.0	15	100.0	0.0	0.0				
56	12 17.5	130 42.5	22	12.0	53.2	34.8	76.9	23.9		
57	12 17.5	130 40.0	18	0.9	82.0	19.1	70.0	9.4	80.6	59.9
58	12 17.5	130 37.5	24	23.8	51.6	24.6	59.5	26.3		
59	12 17.5	130 35.0	24	9.9	56.8	32.3	71.5	24.7	73.9	55.9
61	12 17.5	130 30.0	24	36.7	47.1	16.1	74.7	24.3	88.5	71.6
62	12 17.5	130 25.0	27	10.0	53.5	36.5	63.7	25.0		
63	12 15.0	130 47.5	15	17.1	64.5	18.6	85.7	25.0		
65	12 15.0	130 42.5	20	12.5	87.0	0.5	89.5	26.0	95.9	90.0
66	12 15.0	130 40.0	24	7.9	68.9	23.2	80.5	22.3		
67	12 15.0	130 35.0	30	19.3	62.2	18.5	81.2	26.1		
68	12 15.0	130 32.5	30	9.1	77.6	13.3	70.9	25.5		
69	12 15.0	130 30.0	24	2.1	97.6	0.3	61.7	16.5	91.4	62.2
70	12 15.0	130 27.5	27	33.5	48.3	18.2	70.5	24.3		
71	12 15.0	130 25.0	32	4.1	47.4	13.8	66.5	23.2		
72	12 15.0	130 20.0	34	4.8	78.4	16.8	59.4	26.1		
73	12 12.5	130 50.0	18	14.0	64.8	21.2	86.1	25.4		
74	12 12.5	130 47.5	16	14.7	66.5	18.8	73.4	21.8		
75	12 12.5	130 45.0	20	13.9	71.6	14.5	79.9	25.8	87.4	73.1
76	12 12.5	130 42.5	18	3.9	96.0	0.1	87.4	-		
77	12 12.5	130 40.0	22	14.6	70.3	15.1	73.9	24.9		
78	12 12.5	130 37.5	27	21.3	65.4	13.3	81.2	29.2		
79	12 12.5	130 32.5	27	21.6	63.8	14.5	75.9	26.8		
80	12 12.5	130 30.0	43	18.7	73.8	7.5	77.1	35.4	90.4	76.5
81	12 12.5	130 27.5	30	53.2	40.8	6.0	78.7	27.6		
82	12 12.5	130 22.5	34	66.2	22.4	10.7	51.4	27.5	83.5	69.7

Station	Latitude	Longitude	Water Depth(m)	%gravel	%sand	%mud	% Carbonate Sand	Mud	Gravel	Total
90	12 10.0	130 22.5	34	59.0	34.4	6.6	76.8	32.2		
Stations off Darwin, HMAS Cook, Feb/Mar 90										
007	12 00.0	130 05.1	54	19.9	73.7	6.4	55.6	27.1		55.0
009	12 05.0	130 15.1	49	3.6	94.5	1.8	53.5	25.0		27.6
017	12 10.0	130 25.1	36	21.6	67.4	11.0	66.0	34.3		66.6
023	12 20.0	130 39.9	23	0.0	43.9	56.1	71.3	34.1		51.1
024	12 19.9	130 45.0	20	2.3	88.0	9.7	57.7	24.2		50.3
025	12 13.4	130 37.3	32	13.6	70.2	16.2	71.7	25.5		62.7
Stations off Darwin, M. V. Malita Nov/Dec 1960										
2	12 20.3	130 41.0	20	11	58	31	72	24		53
3	12 16.0	130 33.7	27	1	64	35	89	26		54
4	12 12.0	130 25.6	47	15	59	26	85	29		73
5	12 07.9	130 18.0	40	32	57	11	66	30		73
66	12 18.1	130 28.5	27	13	66	21	85	18		73
165	12 11.5	130 16.6	33	53	40	7	100	33		95

Average bulk sediment densities over the length of the cores obtained off Darwin in Feb/Mar 90:

Station No.	7	9	17	23	24	25
Core length(m)	0.170	0.224	0.145	0.370	0.205	0.340
Average density (kg/m^3)	1642	1911	1679	1531	1819	1445

Gravel/sand/mud percentages from the cores obtained off Darwin in Feb/Mar 90:

Stn. No.	Depth in core (m)	Gravel (%)	Sand (%)	Mud (%)
17	0.05 - 0.07	31.74	59.65	8.58
17	0.115 - 0.13	17.77	67.55	14.68
23	0.065 - 0.09	0.11	68.00	31.89
23	0.16 - 0.18	2.23	64.45	33.32
23	0.24 - 0.26	0.51	54.89	44.60
23	0.345 - 0.36	2.32	58.80	38.88
25	0.14 - 0.16	22.04	58.68	19.28
25	0.195 - 0.22	28.24	53.15	18.61
25	0.305 - 0.32	63.40	26.82	9.79

APPENDIX B

Sample descriptions

Station	Colour	Porosity	Sediment Density (g/cc)	Grain Density (g/cc)	Angle of Initial Yield (dec. deg.)	Mz (phi)	σ_1 (phi)
Stations off Broome, Dec.1990:							
2	5Y6/1	0.48	1.753	2.449	33.91		
3	5Y7/2	0.59	1.818	2.998	36.21	1.63	0.56
4	N5	0.53	1.825	2.757	39.43		
7	5GY6/1	0.50	1.889	2.780	35.80		
8	5GY2/1	0.52	1.902	2.882	33.91	-0.23	1.10
9	10YR6/2	0.51	1.843	2.723	33.20	1.03	0.75
10	10YR4/2	0.50	1.770	2.541	37.03	1.58	1.23
11	N3	0.48	1.651	2.253	39.02	0.12	2.26
12	5B5/1	0.55	1.794	2.766	32.77	2.30	0.66
13	5G4/1	0.55	1.866	2.927	36.27		
14	5G4/1	0.44	1.933	2.667	39.52		
15	5Y4/1	0.50	1.910	2.821	27.77	0.18	1.88
16	5B5/1	0.49	1.796	2.563	40.15		
17	5GY6/1	0.52	1.929	2.937	35.67		
18	5GY6/1	0.59	1.715	2.747	36.92		
19	5Y6/1	0.56	1.681	2.551	40.22		
20	5G6/1	0.49	1.810	2.590	37.30	0.78	1.59
21	5G6/1	0.50	1.882	2.765	39.71		
22	5B5/1	0.52	1.936	2.953	33.65		
23	N3	0.48	2.008	2.940	41.42		
24	5G2/1	0.49	1.751	2.474	25.00		
25	5Y4/1	0.50	1.856	2.713	36.72	0.68	1.28
26	10Y6/2	0.55	1.812	2.806	36.06		
27	5Y5/2	0.48	1.835	2.607	29.98	1.24	1.52
Stations off Port Hedland, Dec. 1990:							
37	5YR3/4	0.41	1.878	2.489	38.27	1.35	2.07
38	10R4/6	0.56	1.794	2.807	-		
39	10R3/4	0.52	1.762	2.589	33.11	2.75	>2.00
40	5YR3/4	0.57	1.629	2.466	-		
41	5YR4/4	0.42	2.021	2.761	30.62	0.87	1.29
42	5YR4/4	0.46	2.070	2.984	39.11		
43	5YR3/2	0.43	1.868	2.525	34.33		
44	10R3/4	0.47	2.002	2.893	37.85	-1.39	0.86
45	5YR3/4	0.42	1.947	2.635	42.21	>3.00	>4.00
46	5R4/2	0.50	1.888	2.778	38.76	-1.12	1.55
47	5YR4/4	0.47	1.932	2.761	-	2.47	>2.00
48	5YR3/2	0.50	1.782	2.565	34.81		
49	5YR4/4	0.41	2.098	2.862	35.05		
50	5YR4/4	0.50	1.902	2.805	29.25	2.58	1.91
51	5YR4/4	0.47	1.900	2.699	36.80	0.31	1.20

Station	Colour	Porosity	Sediment Density (g/cc)	Grain Density (g/cc)	Angle of Initial Yield (dec. deg.)	Mz (phi)	σ_1 (phi)
52	5YR5/2	0.49	1.936	2.837	39.85		
53	5YR5/2	0.53	1.879	2.872	39.82		
54	5YR4/4	0.52	1.905	2.887	35.19	1.41	1.08
56	5YR4/4	0.44	1.910	2.626	34.84		
57	10R4/2	0.49	1.901	2.769	32.86		
58	5G6/1	0.52	1.862	2.797	39.57		
59	5YR5/2	0.47	1.953	2.800	40.85		
60	5YR3/2	0.40	1.902	2.505	37.77		
61	10YR4/2	0.52	1.771	2.608	34.64		
62	5YR4/4	0.51	1.776	2.585	35.30		
63	5YR2/1	0.49	1.861	2.691	36.63	1.08	1.01
Stations off Port Hedland, Feb. 1992							
1	10YR4/2	0.59	1.529	2.294			
2	10YR6/6	0.49	2.190	3.336			
3	10YR4/2	0.71	1.313	2.085			
4	10YR5/4	0.66	1.476	2.405			
5	10YR7/4						
6	10YR2/2	0.44	1.842	2.506			
7	10YR5/4	0.43	1.930	2.633			
8	10YR5/4	0.38	2.006	2.623			
9	10YR5/4	0.37	1.946	2.502			
10	10YR5/4	0.45	1.881	2.604			
11	10YR5/4	0.56	1.711	2.618			
12	10YR4/2	0.50	1.821	2.643			
13	10YR4/4	0.45	1.949	2.727			
14	5YR6/4	0.49	1.834	2.637			
15	10YR4/2	0.42	1.946	2.632			
16	10YR6/6	0.38	2.007	2.625			
17	10YR5/4	0.48	1.828	2.594			
18	10YR4/2	0.44	1.897	2.603			
19	10YR6/6						
20	10YR5/4	0.46	1.892	2.653			
21	10YR5/4	0.48	1.851	2.639			
22	10YR7/4	0.49	1.813	2.596			
23	5YR3/4	0.41	1.970	2.645			
24	5YR3/4	0.43	1.962	2.689			
26	10YR7/4	0.57	1.744	2.732			
27	10YR5/4	0.43	1.969	2.701			
28	10YR5/4	0.52	1.778	2.623			
29	10YR6/6	0.47	1.829	2.566			
30	10YR7/4	0.55	1.720	2.602			
31	10YR5/4	0.50	1.833	2.668			
32	5YR6/4						
33	10YR4/2	0.48	1.813	2.565			

Station	Colour	Porosity	Sediment Density (g/cc)	Grain Density (g/cc)	Angle of Initial Yield (dec. deg.)	Mz (phi)	σ_1 (phi)
34	10YR7/4	0.48	1.851	2.638			
35	10YR5/4	0.51	1.774	2.582			
36	10YR2/2	0.54	1.737	2.604			
37	10YR4/2	0.45	1.778	2.416			
38	10YR6/6						
39	10YR4/2	0.51	1.850	2.736			
40	10YR5/4	0.50	1.860	2.721			
41	10YR5/4	0.55	1.757	2.684			
42	10YR5/4	0.48	1.862	2.659			
43	*						
Stations off Darwin, LCM-8, Feb. 1992:							
46	10YR4/2	0.313	2.08	2.58	36.03	Median Phi = -1.78	
48	10YR4/2	0.447	1.89	2.62	33.57	-0.21	1.83
50	5Y4/2	0.566	1.58	2.35	22.19		
51	10YR4/2	0.442	1.95	2.71	39.73	Median Phi<-2.0	
52	10Y4/2	0.480	1.76	2.47	33.63		
55	100%GRAVEL	---	----	----	----		
56	10Y4/2	0.591	1.58	2.41	28.51		
57	10Y4/2	0.556	1.59	2.33	33.70	2.72	1.67
58	10Y5/4	0.460	1.71	2.31	27.53		
59	10Y4/2	0.557	1.53	2.21	42.83	Median Phi=2.65	
61	10Y4/2	0.473	1.76	2.44	40.81	0.78	2.99
62	10Y4/2	0.597	1.53	2.33	40.10		
63	10Y4/2	0.543	1.62	2.35	40.50		
65	5Y6/4	0.623	1.60	2.59	41.34	0.36	1.00
66	10Y4/2	0.571	1.61	2.43	41.86		
67	5Y4/4	0.553	1.66	2.49	34.85		
68	10Y6/4	0.562	1.60	2.37	45.28		
69	10YR4/2	0.519	1.78	2.62	38.04	0.71	0.72
70	10Y4/2	0.445	1.84	2.52	37.38		
71	10Y4/2	0.497	1.70	2.39	35.96		
72	10Y4/2	0.518	1.63	2.31	19.89		
73	10Y4/2	0.482	1.76	2.47	38.74		
74	5Y5/6	0.498	1.74	2.48	31.80		
75	10Y4/2	0.486	1.80	2.56	31.56	1.50	2.20
76	10YR5/2	0.480	1.84	2.61	32.61		
77	10Y5/4	0.462	1.77	2.44	24.98		
78	10Y5/4	0.502	1.76	2.52	34.55		
79	10Y5/4	0.458	1.77	2.42	40.49		
80	10Y4/2	0.474	1.85	2.61	35.90	0.89	1.88
81	10Y4/2	0.457	1.80	2.47	34.95		
82	10Y4/2	0.471	1.90	2.70	35.58	Median Phi=-1.75	
90	10Y4/2	-----	----	-----	37.43		

Station	Colour	Porosity	Sediment Density (g/cc)	Grain Density (g/cc)	Angle of Initial Yield (dec. deg.)	Mz (phi)	σ_1 (phi)
Stations off Darwin, HMAS Cook, Feb/Mar 90							
007	10YR4/2	0.451	1.98	2.78	23.51		
009	10YR5/4	0.398	1.99	2.65	32.70		
017		0.518	1.81	2.69	-----		
023	5B5/1	0.658	1.52	2.53	*		
024	10YR4/2	0.527	1.77	2.62	43.23		
025	5G4/1	0.559	1.65	2.48	*		

* At stations 23 and 25 mud contents were high and angles of initial yield were not obtainable. Unconfined compressive strengths, obtained in the laboratory with a Geotester pocket penetrometer, were 2.44 kPa and 4.87 kPa, respectively.

Stations off Darwin, M. V. Malita Nov/Dec 1960

		Mean Phi	Median Phi	Std. Dev'n.
2	5GY5/2	2.15	2.35	2.47
3	5GY5/2	3.30	3.02	1.83
4	5GY5/2	2.00	2.45	2.37
5	5GY5/2	0.67	1.60	2.44
66	------	1.48	1.61	2.22
165	10Y4/2	0.86	1.28	2.17

Colour codes are explained fully in the Rock Color Chart of the Geological Society of America, but in the range of soil colours encountered in this work:
the 10Y's were olives;
the 5Y's were olive greys and olive browns;
the 10YR's were browns and oranges;
the 5YR's were reddish browns;
the N's were neutral greys;
the 5GY's were greenish greys and yellow greens;
the 5B was bluish grey;
the 5G's were greenish greys;
the 10R's were reddish browns and greyish reds;
the 5R was greyish red.

ACCURACY

Porosities of sediment samples were measurable to an accuracy of approximately 2%, sediment grain densities to an accuracy of approximately 6%, and angles of initial yield to an accuracy of approximately 3.5 %. The % variation between samples taken within a few metres radius of a given location may be larger than this, as may be the variation over time at a fixed location.

APPENDIX C

Millimetres versus ϕ units

Millimetres:	256	128	64	32	16	8	4	2	1	0.5	0.25	0.125	0.062
ϕ units	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4

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Marine sediments Sediment properties Sea floor

ABSTRACT

To investigate the likelihood of mine burial by various mechanisms in northern and north-western port approaches, sea floor sediment samples were obtained on a number of research cruises off Broome, Port Hedland and Darwin. In this report the results of analyses on these samples, to obtain a range of relevant sediment properties, is presented. The mine burial estimates derived from these results will appear in a companion, classified report. The sea floor in the approaches to both Broome and Port Hedland consists predominantly of carbonaceous sand, and off both these ports the bottom is so hard at a significant number of locations that only small sediment samples were obtainable, even after several attempts with a grab. In the approaches to Darwin the most common surface sediment type is muddy sand, however there are also broad areas of sandy gravel, gravelly sand and sand, and at some locations there is a shallow surface sand layer underlain by a more muddy one.

Sediment Properties off Broome, Port Hedland & Darwin

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