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Heron Island Spoil Dump

M.R. Gourlay and J.S. Jell

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Great Barrier Reef Marine Park Authority

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A REPORT TO THE GREAT BARRIER REEF MARINE PARK AUTHORITY

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Executive Summary

The Heron Island harbour was re-dredged between September and November 1987 and a swing basin for vessels and a jetty were also constructed at that time. Following concern about the potential effects of the dredging operation, a multi-disciplinary monitoring program was initiated. This report covered the investigation into the nature and distribution of sediments on the reef flat and in the spoil dump, the conditions responsible for the erosion of the spoil dump and the quantity of dredge material in the spoil dump.

Generally, the dredging operation suspended large quantities of fine material which settled south of the spoil dump and particularly along the outer edge of the reef. The dredge material did not appear to affect the area east of the Research Station on the south of the cay and east of the resort on the north of the cay. In the two years following the dredging, much of the fine material was redistributed and removed from the reef flat by natural action. The sediment distribution patterns appear to be returning to those prior to the 1987 dredging operation.

Cyclone Fran was generally responsible for removing a large amount of silt from the reef flat and from the harbour channel itself, thus further acting as a cleansing agent for reef flat biota.

The quantity of dredge spoil deposited on the beach was estimated at 14,860m^3. The spoil dump eroded rapidly in the first 5 months following dredging with around 6% of the total volume lost. Over the following 3 years this tapered off to around 11% of the initial spoil dump volume. Major climatic events such as storms and cyclones can still cause substantial erosion to occur from the spoil dump. During Cyclone Fran in March 1992, a further 4% of the total volume was lost and the shoreline underwent substantial re-alignment.

Silt in the spoil dump is concentrated in lenses. These lenses are generally more prevalent in the northern side of the spoil dump which is also the side most prone to erosion. The top of the spoil dump is very rubbly, making it unpleasant to walk on and difficult for turtles to nest in.

The environmental conditions causing silt plumes to be produced from the spoil dump were studied intensely over a 3 year period. Wave height and tidal state were the most important variables affecting erosion. The conditions causing the formation of silt plumes are episodic and have been decreasing over time, so that now they only occur at wind speeds greater than 15-20 knots, coinciding with tide levels of more than 2.5m.

Recommendations are made for the management of the spoil dump and for further monitoring.

PART ONE

Short term monitoring and environmental effect

1. INTRODUCTION

Heron Island is located in the Capricorn Group of reefs, which together with the Bunker Group, form the southernmost part of the Great Barrier Reef Marine Park (Figure 1). In this region the Reef consists of a series of isolated platform reefs, many of which have small vegetated islands (coral cays).

Heron Reef is about 9km long and 4km wide at its widest point. It has a lagoon and Heron Island is situated on the leeward side of the western end of the reef platform. The island itself, which is formed of calcareous material, mainly sand, is 830m long and 300m wide and is approximately elliptical in outline. It is aligned with its long axis in the direction eastsoutheast - westnorthwest. Its maximum height is 8m above low water datum. Sandy beaches surround the cay although on both the northern and southern sides there are substantial outcrops of beachrock. The processes whereby cays such as Heron Island are formed have been reviewed elsewhere (Gourlay 1988).

The island is one of the most visited reef islands, being one of the three coral cays in the Great Barrier Reef Marine Park with tourist resorts. It also is the location for a marine research station and a substantial part of the island is a national park. Activities associated with these uses generate a considerable number of passenger journeys between the island and the mainland by either boat or helicopter as well as many boat journeys locally. The need to provide upgraded facilities to handle the boat traffic necessitated the expansion of the capacity and facilities associated with the boat harbour.

During September to November 1987 the boat harbour at Heron Island was enlarged and dredged. Material was removed by excavator and by suction dredge. The majority of the spoil from this work was dumped on the beach south of the helipad. The existing beach material was pushed aside to allow dredged material to be pumped into a ponding area.

Concern has been expressed over the quantity of fine material which emanated from this exercise, both during the initial dredging and subsequently from the dumped material on the beach. There are three aspects to the concern about the presence of fine material on the reef:

(i) the presence of fine material in the sea water may affect the light available to marine organisms;

(ii) the fine material may settle onto the organisms and adversely affect their life processes;

(iii) the fine material may form an anoxic layer on the reef detrimental to the infauna.

Following a request from the Executive Officer of the Great Barrier Reef Marine Park Authority the authors made a preliminary inspection of the dredge spoil dump in May 1988 and submitted a report on its condition together with a proposal for short term monitoring of it for a period of twelve months (Gourlay and Jell 1988). The monitoring programme included the following activities:

(i) Assessment of the nature and quantity of material within the spoil dump.
(ii) Monitoring of the stability of the spoil dump.
(iii) Monitoring of conditions affecting the spoil dump.
(iv) Determination of nature and concentration of material forming silt plumes.
(v) Extent and rate of lithification of the spoil dump material.
(vi) Monitoring of reef flat sediments.
(vii) Monitoring of beach rock.

After some administrative delays the contract for the short term monitoring programme was finalised in November 1988 and work began in December 1988. Subsequently arrangements were made to extend short term monitoring activities initially to June 1990 and later to 30 April 1991.

This report first reviews the events associated with the construction of the boat harbour. It then outlines the investigations made for the monitoring programme. The results of the analyses of the data collected during these investigations are discussed in detail. Finally the overall situation is assessed, conclusions stated and recommendations for further action and long term monitoring are made.

Because of the extensive and repetitive nature of much of the experimental data, only the more significant parts of it are presented in this report.

A summary of the monitoring programme and its results up to 30 April 1990 has been presented separately (Gourlay 1991b). The nature of the coastal observations made during the monitoring programme, together with some typical results, are reviewed in Gourlay (1991a).

The scope of this investigation was limited to geomorphological and sedimentological aspects of the spoil dump and its environmental impact. The impact of the spoil dump upon the biology of the reef adjoining the boat harbour and the island has been investigated separately. Fisk (1990, 1991) has reported on the implementation of a monitoring programme for reef flat benthos. Catterall et al. (1990) have investigated the impact of dredging upon one benthic species, the volute *Cymbiolacca pulchra*, and its environment, using data from annual surveys made predredging (1984 to 1986), during dredging (1987) and postdredging (1988 and 1989). A study by Heron Island Research Station (HIRS) over a three year period subsequent to dredging has monitored coral and other benthic communities on the beach rock, the nutrient regime of water surrounding the cay under various conditions, and the average rates of sediment deposition at various stations on the reef flat around the island at two monthly intervals. Results of the HIRS study are not yet available (November 1991).

2. HERON ISLAND BOAT HARBOUR AND ITS GEOMORPHIC SETTING

2.1 Works Constructed Prior to 1987

The situation and problems associated with Heron Island dredge spoil dump are the latest phase of a series of impacts and interactions between the natural processes which formed and which are continually reshaping coral cays and various engineering works and other human activities at Heron Island (Figure 2) during the last 50 or more years (Gourlay and Flood 1981; Gourlay 1983b). The impacts of cyclones and climatic variations on a secular time scale of 10 to 30 years have resulted in movements of the shoreline of the western end of the island from a northwesterly position in 1936 to a southwesterly one in October 1966 prior to the initial construction of the boat harbour (Flood 1974, 1981, 1986). This movement was associated with the loss of sand from the island and reef platform as ebb tide currents drained seaward through a gap in the reef rim, blasted in 1945, at the location of the entrance to the present boat harbour. It also required the construction during the 1950s and 1960s of a seawall to protect resort buildings on the northwestern side of the island.

Dredging of the original boat harbour during late 1966 and early 1967 was interrupted by cyclone "Dinah" which partly infilled it and the project was not completed until October 1967. Material dredged from the boat harbour was used to reinstate the sand spit on the western end of the island. Subsequently, the helipad was built on this reclaimed area in 1968. While there are no records available, this whole operation must have created considerable environmental disturbance and the reclaimed sand spit would have been in many ways similar to the spoil dump created from the more recent operations. However, it is unlikely that any attempt was made then to confine the silt generated by the dredging operation and the disturbance created by cyclone "Dinah" may well have removed most of it from the beach and indeed from the reef platform itself.

Subsequently, the low rubble walls surrounding the boat harbour were damaged by cyclones in 1971 and 1972, culminating in the partial infilling of the boat harbour by cyclone "Emily" in early April 1972. Maintenance dredging was carried out in October 1972 and the material removed from the harbour placed in front of the rock seawall on the northwestern side of the island. The harbour was again partially infilled with sediment by cyclone "David" in January 1976 and more sediment was deposited in it by cyclone "Simon" in February 1980. During this period, tidal currents spilling through gaps in the walls surrounding the harbour were also depositing sand in it. Maintenance dredging was again undertaken between November 1980 and February 1981, the dredged material being placed behind the timber seawall originally constructed in 1970 to protect the helipad. In 1982-83, two hundred 2 tonne concrete blocks were placed in two rows, one to the north and the other to the south of the harbour in an attempt to block the outflow of tidal currents through the boat harbour.

There are no recorded observations of environmental disturbance caused by the release of fine silt from the maintenance dredging operations or from the dredged material placed upon the cay's shoreline during these earlier works.

2.2 Boat Harbour Enlargement Works 1987

The project for maintenance dredging and enlargement of the boat harbour commenced around 14 September 1987 and was finished by the second week in November 1987. Most of the dredging was completed by the middle of October 1987. A further minor enlargement of the harbour was undertaken between 19 and 21 February 1988. The main project included the construction of a timber jetty and some maintenance of existing bund walls surrounding the harbour (Figure 3).

The enlargement of the harbour was undertaken at low tide by an excavator which broke up coral rubble and other large material and deposited it in a vehicle for removal to the spoil dump area or various locations along the bund walls. A cutter suction dredge operated within the boat harbour and access channel to remove material deposited in them. Dredged material was pumped ashore and deposited in the spoil dump area south from the helipad in front of the research station (Photos 1 and 2).

The original intention was to stockpile sand from the beach south of the helipad and to build a settling pond there for the dredge effluent discharge. However, the beach was found to be composed mainly of rubble with a relatively thin cover of sand.

The exact details of the construction and operation of the settling pond were not recorded at the time but it appears that rubble materials from the beach and from the harbour excavation were used to form a bund wall which was initially open at its northern end (Photo 3). Observers on the island reported that the dredge effluent including most of the fine sediment flowed back directly into the boat harbour for at least a week.

The open end of the pond was then closed and pipes inserted at the bottom of the bund to discharge the effluent from the pond back into the harbour. This arrangement was not much better than the open pond.

Following an inspection by the supervising engineer, the overflow pipes were repositioned on 8/9 October at the top of the bund so that a proper settling pond was formed (Photo 4).

The mode of operation of the original settling pond was such that little fine material was likely to have been deposited in it. Indeed information has been given that, during the operation of the pond, a 200mm thick layer of fine silt/clay, like a cement slurry in appearance, was deposited at the outlet of the settling pond in the present boat ramp area between the helipad and the jetty. This layer was of the order of 100mm thick in December 1987. Most of this material had disappeared by May 1988 although some fine material apparently remained on the reef flat between the northern harbour bund wall and the northern line of concrete blocks. The effectiveness of the final settling pond arrangement is unknown but presumably a greater proportion of the fine sediment from the dredge effluent was retained in the spoil dump.

After completion of the dredging, the rubble bank was pushed down and the available sand spread over it to form a beach on its present location. The permit for the project allowed the beach toe to be moved 30m seaward from its pre-existing location. The beach was to be restored to its original condition with an upper surface of soft unconsolidated beach sand. This did not occur. As noted by Kinsey in early 1988 "In reality the surface is now hard compacted shingle with some sand. It is particularly unyielding and can not in realistic circumstances be walked on by tourists in bare feet". (Kinsey 1988).

2.3 Geomorphic Setting of Heron Island

Before describing the investigations for the spoil dump monitoring programme, it will be helpful to describe the geomorphic setting of Heron Island, in particular the nature of the reef flat which surrounds it.

Heron Reef is a typical lagoonal platform reef and geomorphically can be subdivided into the 'reef slope' below the line of intersection of the reefal mass and the water surface at low tide, and the 'reef top' above and inside this line (Jell and Flood 1978). Heron Island is a sand cay developed on the leeward end of the reef top. The reef top includes the outer "Reef Rim" which is the highest part of the intertidal portion of the reef being a few centimetres above the upper level of coral growth. It is almost continuous around the reef except for a few places on the western and northeastern margins. The harbour is a major breach in the rim and controls the ebb tide currents. The reef rim is not well developed for the first 100m eastsoutheast of the wreck (Figure 4). The reef rim varies from 20 to 80m in width on the western end of Heron Reef and can be subdivided into an outer coral/algal zone, an outer moat, and an inner rubble zone. This is a high energy zone and sand size sediment is restricted to the potholes, crevices and interstices between the rubble. Algal turf entraps considerable quantities of sediment of fine sand to silt size. Sediment in this area varies considerably from one sample site to another and is not significant in this study.

The Reef Flat is that portion of the reef top which is exposed during low tides and extends inwards from the rubble zone of the reef rim. It consists of:

(i) an outer coral-algal zone of living coral with extensive algal encrustations and sheets of coral shingle, with sand patches restricted to coral pools and shallow channels which are commonly arranged normal to the refracted wave fronts;

(ii) a coral-sand zone containing fewer stands of living coral, with dead coral commonly encrusted by both corraline and fleshy algae;

(iii) a sand zone typified by broad expanses of sand, with sparse clumps of living coral interspersed with patches of dead coral; the sediments are continually being bioturbated by holothurians.

On the western end of Heron Reef the coral-algal zone is 15 to 105m wide on the southern side and up to 275m on the northern reef flat. This merges with the coral-sand zone which may be 50m to 250m in width. On the northern side the sand zone is up to 500m in width but is much narrower on the southern side. Sediment is transported across the reef flat as evidenced by the sand waves or ripples and samples taken at any one locality are representative of that area. To the east of the island the sand zone of the reef flat merges with the broad sandy shelving area below low water level. This is the shallow lagoon and represents a prograding sand wedge into the deeper lagoon of the central part of the reef top.

Heron Island is the sand cay formed of supratidal deposits on the reef flat at the western end of the reef top. It rises abruptly from the southern reef flat to a maximum height of 8m above low water datum and then slopes gently northwards. A sandy beach, 15 to 30m wide at low tide, surrounds the cay. This in turn is partly surrounded by beach rock, 9 to 21m in width on the southern shore, 3 to 6m wide in the north and west. On the southern side the beach rock is bordered by a shallow moat which is 15 to 30m wide and consists of a sandy floored depression approximately 80cm below the general level of the reef flat. The moat represents the plunge line of the main body of breaking waves and is caused by wave scour. A large sand spit is developed off the northeastern side of the island and is exposed at low tide.

There are no recent or extensive hydrographic surveys of the reef flat and only a very general impression of its elevation can be given. The general level is 0.6 to 0.8m above low water datum (see section 3.4) with the region either side of the boat harbour originally being lower than this. The level of the top of living corals at the western end of the moat opposite the end of the presently exposed beach rock is 1.0m above low water datum. The reef rim is probably at least this elevation.

Details of the geomorphic, ecological and sedimentological zonation of Heron Reef are discussed by Jell and Flood (1978). These authors also provide maps of the distribution of the zones, especially for the western end of the reef which is relevant to this study.

3. INVESTIGATIONS

3.1 Objectives of Monitoring Programme

The overall objectives of the monitoring programme described in this report were to determine the following:

(i) the nature of the material stored within the spoil dump, the nature of the material released in the silt plumes and deposited on the reef flat, together with the extent and persistence of fine silt deposits on the reef flat;

(ii) the total amount of material stored within the spoil dump, the magnitude of losses occurring from it, the changes in its shape and their implications for shoreline stability;

(iii) the hydraulic and meteorological conditions responsible for reshaping the spoil dump and releasing silt from it and the frequency of occurrence of silt-producing events.

Having determined the nature, magnitude and causes of the continuing problem, it would then be possible to make recommendations concerning the future management of the spoil dump and any further monitoring activities required.

3.2 Field Work

Field work for this project was undertaken in two different ways:

(i) special visits to the site by the investigators;
(ii) continuing observations on site by Heron Island Research Station (HIRS) personnel.

Site visits were made as follows:

13-18 May 1988	Dr Gourlay
17-21 May 1988	Dr Jell
3-19 December 1988	Dr Jell
29 March to 7 April 1989	Dr Gourlay and Mrs Hacker
2-8 December 1989	Dr Jell
2-6 January 1990	Dr Gourlay
10-16 August 1990	Dr Jell
24-30 November 1990	Dr Jell
17-24 June 1991	Dr Gourlay

Dr Gourlay's site visits included surveying the spoil dump to determine changes to its size, etc., while Mrs Hacker investigated the nature of the material contained in it. Dr Jell collected sediment samples from the reef flat and observed the condition of the beach rock. Dr Jell had sampled the material in December 1987.

Observations of waves and other factors associated with the occurrence of silt plumes have been made by HIRS personnel commencing in December 1988 and continuing on a daily basis since early 1989. These observations are still being made. HIRS personnel also from time to time made measurements of the turbidity of the water over the reef flat.

The site visit during March-April 1989 was originally planned to take place earlier in the year to coincide with the scheduled excavation of a trench across the spoil dump for the construction of the research station's new saltwater intake pipeline. It was intended to monitor this operation and record details of spoil dump sediments exposed during this activity. Delays in the pipeline project resulted in a change in plans and the site was visited before this operation occurred. Instead arrangements were made with the contractor constructing the pipeline to excavate temporary holes in the spoil dump for inspection purposes. At the time of this visit the excavation for the new pumphouse was also still open and this allowed examination of natural cay sediments behind the spoil dump. Details of the subsurface investigations are given in section 4.1.2.

3.3 Sedimentological Analyses

The sedimentological analyses were undertaken to determine the nature of the material stored in the spoil dump, the nature of the material released in the silt plumes and deposited on the reef flat, and the extent and persistence of fine silt deposits on the reef flat.

Sedimentological samples were obtained from the spoil dump during the subsurface investigations (section 4.1.2). Samples were also taken across the reef flat at intervals of 50m on nine traverses (Figure 4) on several occasions. Traverses A, B, G, H and I were taken in the area most likely to be affected by material from the dredging operation and from erosion of the spoil dump. Traverses C, D, E and F were taken to monitor areas away from the harbour and spoil dump, in order to ascertain if the material from the dredging was widely distributed, and also to determine changes in the sediment distribution in these areas that occur because of changing hydraulic conditions across the western end of the reef. All samples were taken by scooping a screw topped jar through the top 2 cm of sediment and applying the lid immediately so as to lose as little of the fines as possible.

On each traverse, samples were collected from the larger areas of sediment commonly showing ripple marks, rather than from small isolated patches between or within coral clumps or within the rubble material. All previous surveys used 50m sampling intervals and showed consistent gradients in parameter values. This suggests that the sampling procedure for reef flat sediments was appropriate.

A total of 388 sediment samples were either collected specifically for this project or were available from previous investigations. 308 sand size samples were sieved at 0.5ϕ intervals to give grain size distributions of the sand fraction. 22 samples were analysed using laser diffraction analysis to determine the grain size distribution of the silt fraction of samples or the size distribution of suspended solids from water samples. Where necessary the results of the sand and silt grain size distributions obtained from these two types of analysis were combined to give a single grain size distribution. Size distribution analysis was not undertaken for particles greater than 4mm.

The procedures used for the preparation of the samples for particle size analysis were as follows:

(i) Samples were treated with bleach (10% NaOC1) to remove organic material.

(ii) Samples with a significant proportion of fines were wet sieved through a 63μm (4ϕ)sieve. The fine residue was allowed to settle, water was decanted and the wet sieve residue (WSR) air dried.

(iii) The material retained on the 63μm sieve and the samples which were not wet sieved were oven dried ($\leq$100^{O}C).

(iv) Both the retained material from the wet sieved samples and the other samples were sieved through 0.5ϕ sieves with a range from -2ϕ to 4ϕ (4mm to 63μm). The fine residue from this operation is designated the dry sieve residue (DSR). All sieve fractions have been kept.

(v) Both WSR and DSR were analysed with the laser size analyser and the results combined with those from the sieve analysis to give grain size distributions for the size range 9 to -2ϕ (2μm to 4mm).

(vi) Grain size distributions were plotted using software compiled using FORTRAN and HGRAPH. Each plot shows a histogram of proportions of each particle size fraction and a cumulative size distribution curve. Both ϕ and mm sizes are indicated with mm size increasing from left to right in accordance with normal engineering practice.

(vii) Where required for detailed comparison of sediment size distributions, e.g. on the reef flat, the standard statistical parameters, i.e. graphic mean and graphic standard deviation, were computed for each grain size distribution using the method of Folk and Ward (1957).

The equipment used to determine the size distribution of the material finer than 63μm was a Malvern laser size analyser. The software used in operating the system allows 16 size ranges to be measured within the range of the lens used. For this investigation two lenses were used - the 100 lens which measures particles in the size range 1.9 to 188 μm and the 300 lens which measures the size range 5.8 to 564μm. Particles larger than the upper limit of the size range are not detected by this instrument but it does give an indication of the proportion of material finer than the designated size range. The laser size fractions were converted to standard 0.5ϕ fractions before the grain size distributions were plotted.

The laser size analyser used only a very small subsample (≈1g) of the total sample and care was required to ensure that a representative subsample was collected. For example subsamples were taken from what appeared to be typical portions of the sample and, where appropriate, the sample was well mixed or shaken before subsampling. Very wet samples were sampled speedily after shaking, using a pipette. Repeat analyses of the same subsample using the same lens gave similar results but sometimes there were discrepancies when different lenses were used. For 16 samples two or more subsamples were analysed independently and for 12 of these samples, analyses of given subsamples were repeated. The results were generally found to be consistent. If any of the inconsistencies were due to limitations of the methodology those results were rejected. The combined grain size distribution curves were sometimes rather strange in form. Microscopic examination of selected samples where this effect was most pronounced indicated that for the wet sieved residue fine silt material was aggregated or clumped together. Small particles were clumped together and several small particles often adhered to larger particles. Hence the grain size distribution of this material is shifted towards the coarser size fractions - coarse silt and fine sand. It is probable that this is a result of the washing/drying process used in the laboratory and consequently greater reliance was placed on the size analysis of fine material which had not been subjected to any drying process. To what extent this clumping occurs naturally is not known.

A total of 21 water samples were collected for the purpose of determining concentrations of silt in silt plumes. Unfortunately not many such samples were obtained and those that were obtained were not always useful. The samples were analysed by the Chemical Engineering Department, The University of Queensland to give the concentration of suspended solids in g/L. Four of these samples were also analysed using laser diffraction analysis to give grain size distributions of the suspended material in the silt plumes.

3.4 Surveys of Spoil Dump Size and Shape

The surveys of the spoil dump size and shape were undertaken to determine the total amount of material stored within it, the magnitude of losses occurring from it, the changes in its shape and their implications for shoreline stability.

The location of the shoreline of the spoil dump and changes in its volume were obtained from the four field surveys made in May 1988, April 1989, January 1990 and June 1991. The total volume of material within the spoil dump was estimated by comparison with the August 1984 survey by the Department of Harbours and Marine (DHM 1984).

Surveys were made by the stadia method using a Sokkisha B2 automatic level and a 5m extendable aluminium staff, this equipment being available at the research station. It was found impossible to locate suitable fixed reference points in the spoil dump so each survey had to be recommenced from reference points on the helipad and the end of the resort seawall. This difficulty arises from the various uses being made of the spoil dump from time to time - as a storage area for building material or boats which block lines of sight - or the movement of vehicles over it and the regrading of eroded areas to facilitate this movement which is likely to displace any reference marks left in situ. Placement of marks on the landward side of the spoil dump is also not an option as levels and sight distances are unsuitable for the available surveying equipment and visibility is restricted by vegetation.

The benchmark for levels on the island is PM 61221 which is located at the centre of the helipad. Its level is 4.511m on low water datum, the latter being located below reef flat surface level. Low water datum is convenient for surveys of the spoil dump and cays in general since all levels are positive numbers. Both the location of the benchmark on the helipad and the proximity of the spoil dump meant that surveying activities had to be planned around helicopter operations - and nonoperations - since a helicopter parked on the centre of the helipad could be an impediment to survey activities. For each survey a series of temporary star picket pegs was placed around the outside of the generally level surface of the spoil dump and located relative to one another by triangulation. After some initial omissions, all locations were checked by backsights to two other pegs wherever possible. Sight distances were restricted as far as possible to 50m to give locations to 0.5m and elevations to 0.01m.

Some difficulty was experienced in surveying profiles of the spoil dump beach as the level difference between the edge of the sand at the base of the beach and the top of the spoil dump was too much to be measured from one location with the available equipment. Additional secondary reference pegs were required lower down the beach for this operation.

Each day's work was planned to fit in with helicopter operations, the tide, availability of research station personnel to assist with holding the staff, etc.. On completion of each day's field work, the results were reduced and plotted that evening. Subsequent days work were planned to fill in any gaps noted until the survey covered the whole spoil dump. About 12 to 16 hours field work spread over 3 to 4 days was generally required to complete each field survey.

Contoured plans to a scale of 1 in 500 have been prepared for each survey. The original plans show the spot levels but the latter are omitted from the figures presented in this report (Figures 5, 6, 7 and 8). As well as determining the shape of the spoil dump the opportunity was taken to accurately locate any identifiable natural features or artificial constructions close to the spoil dump.

Changes in the shape of the base of the spoil dump beach were surveyed directly for comparison with information available concerning shoreline location before enlargement of the boat harbour. For the determination of the spoil dump volume and changes to it, a set of standard lines 10 or 20m apart was superimposed on the contoured plans and crossectional areas along each line above datum level calculated. The volume of material between each pair of lines was obtained by multiplying the average of their areas by the spacing between them. These incremental volumes were then either summed over the total area covered by the profiles to obtain a total volume for each survey or compared directly with the corresponding volume for other surveys to determine the volume change for that portion of the spoil dump.

Additional information concerning changes to the spoil dump was obtained from quasivertical aerial photographs taken from time to time by Queensland National Parks and Wildlife personnel on surveillance flights. In this case black and white negatives were made from the colour slides supplied and enlargements printed at a scale of 1 to 2000 for comparison with earlier observations of the shoreline position. One of the photographs taken in December 1987 is particularly significant as it gives the only known record of the shape and location of the spoil dump soon after its completion and before any significant erosion of its seaward face had occurred (Photo 5). The location of both the base of the spoil dump and the top of the wave-formed scarp/berm on 7 December 1987 were determined from the photograph and, after comparison with levels on the reef flat and the top of the spoil dump surveyed in May 1988, it was possible to determine the initial volume of the spoil dump.

The initial volume is not as reliable as those determined subsequently by direct survey, although two independent estimates by different persons gave values which differed by less than 1%. Errors of between 100 and 200m^3, that is of the order of 1% of the total volume, are to be expected. These are of the same order of magnitude as the measured volume changes between each survey. Nevertheless the latter reduce consistently showing little evidence of the effect of random errors (see Table 2 and Figure 11).

In the vicinity of the jetty, the piles of the jetty are used as reference points. However, it should be noted that the two pairs of piles at the landward end of the jetty, which were not connected by horizontal railings to the other piles, were cut off sometime between May and September 1988. All references to pile numbers in this report refer to piles which extend above deck level to form the supports for the horizontal railings along the jetty. Pile No.1 is located 10m seaward of the concrete slab at the landward end of the jetty.

3.5 Hydraulic and Meteorological Data Analyses.

The hydraulic and meteorological analyses were undertaken to determine the conditions responsible for reshaping the spoil dump and releasing silt from it and the frequency of occurrence of silt-producing events.

The stability of the spoil dump, realignment of the shoreline and release of fine sediments from it are all largely determined by the actual physical conditions to which it is subjected. Tides, waves, winds, currents, rain, etc. may all be involved. These conditions together with observed changes to the spoil dump beach are being recorded daily by members of the Heron Island Research Station (HIRS) staff.

The actual observations and the methods of making them are based upon the COPE programme of the Beach Protection Authority (Robinson and Jones 1977, BPA 1990) and some previous experience over a two week period at Raine Island. The standard COPE observations are made at fixed locations at the same time each day and this procedure was followed by observers on Green Island (BPA 1989). However the observation programme at Heron Island has used two fixed locations and a variable time of observation determined by the time of the day time high tide. There are two reasons for this. Firstly larger waves occur at high tide and observations at that time are more likely to give useful information about the occurrence of silt plumes. Secondly HIRS staff make routine daily observations of water temperature, etc. one hour before day time high water and it was convenient to combine the two sets of observations.

The observations were initiated during December 1988 and reviewed during the field inspection in March-April 1989. Useful information is available from this initial period but complete data is only available from April 1989. In particular the presence or absence of a silt plume was not recorded prior to this date. Observations are made at two stations on the spoil dump and also from the jetty. Separate recording forms are used for each location, copies of which are included in Appendix A. Station 1 is located at the southern end of the spoil dump near the entrance to the research station while station 2 is just south of the jetty. Observations recorded include various characteristics of the waves breaking on the beach (height, period, direction, etc.,) occurrence, width and movement of a silt plume, evidence of erosion and accretion of the beach, tide level and wind strength and direction.

The measurement methods are adapted from those of the COPE programme. Wave heights are visually estimated to the nearest 0.1m; wave periods are averaged over 10 waves by timing the interval between the first and eleventh successive waves with a stop watch; wave directions are measured with a magnetic compass; surf zone and silt plume widths are estimated visually to the nearest 1m.

The daily field observations have been supplemented with Bureau of Meteorology observations from Heron Island automatic weather station (HIAWS). These include three hourly wind speeds and directions, maximum daily wind gust, and twenty four hour rainfalls. Predicted high and low tide levels based upon Harbours and Marine Department tide tables (DHM 1989, 1990) are also used in the analysis of the observations. These predictions are based on Gladstone and the tidal planes, etc are given in Table 1. It should be noted that the zero of the tide board installed on the jetty in April 1989 for this project is 65mm above low water datum used for the tide predictions.

The observed data is forwarded to the University at the end of each month. However this is not always possible owing to problems with HIRS photocopier which prevents the making of a security copy. Indeed delays of several months in transmitting the data have occurred and consequently the analysis programme has also been delayed.

The observed data, together with meteorological and tidal data, is processed in spreadsheet format using Microsoft WORKS. All data is checked as far as possible for consistency and reliability and a number of data plots is made as part of this process. The reliability of the observers is evidenced by the fact that during the period 1 May 1989 to 30 April 1990 observations were made on 363 days out of the possible 365 days.

Over the period of monitoring there has been a number of observers recording the data. On many occasions where apparent inconsistencies were noted, closer examination of conditions indicated that the differences were likely to be real. However, differences in some of the more subjective observations, such as the width of the silt plumes or even the existence of a silt plume, will influence the results of the data analysis. On the other hand, where data could be independently checked, for example wind speed estimates against data recorded by HIAWS, good agreement was obtained on most occasions. A recent assessment of the LEO programme (Smith and Wagner 1991), the coastal engineering observation programme in the United States, indicates that wave heights estimated by observers are likely to be within 30% of correct values and wave period measurements are likely to overpredict the period. The capability of individual observers is the most important factor determining the accuracy of observations. Most of the Heron Island observers have some scientific training.

A considerable number of analyses has been carried out to establish the most suitable forms of presentation. A selection of these is used in the discussion of the results of the analysis. Data is presented in three basic formats - bar charts, scatter plots and time series. Since complete observations are only available since April 1989, the available data was processed initially for the twelve month period May 1989 to April 1990 and analyses were made on a monthly, four monthly or annual basis as considered appropriate. Subsequently data for the second twelve month period May 1990 to April 1991 was processed. The implications of both twelve month analyses are considered in the appropriate sections of this report.

A review of the coastal observation programme, including some typical results, is given in Gourlay (1991b).

Table 1. Tidal Planes at Heron Island Sandard Port Gladstone

Tidal Plane		Elevation above low water datum, m
HAT		3.4
MHWS		2.7
MHWN		2.1
ML		1.61
MLWN		1.1
MLWS		0.6
LAT		0.1
Av. time difference.	HW = –43 min	LW = –38 min
Ratio = 0.70	Constant = –0.01m	

4. RESULTS OF ANALYSES

4.1 Nature and Quantity of Material in Spoil Dump

4.1.1. The Spoil Dump

The material deposited in the spoil dump extends southwards from the jetty for approximately 95m towards the beach rock exposure below the entrance to the Research Station. On the eastern side it abuts against a work area for boats where some revegetation has been carried out. On the seaward side it extends 20 to 30m seaward of the landward end of the jetty where it is bounded by a rubble bank in some places and by an eroded scarp in others. The surface of the spoil dump has been flattened and has a general level of approximately 5.1m.

In April 1989 the erosion scarp, approximately 0.4m high, was comprised of almost pure silt for about 6m adjacent to the jetty. It then merged into rubble with silt for approximately 60m (Photo 6). Approximately 70 to 80m from the jetty the resort maintains a uniform sloping beach for its dive boats to come ashore. Beyond this, the erosion scarp was again developed although less pronounced as it was only 0.2 to 0.3m high and was comprised of interbedded layers of silt, sand and coarser material (Figure 6 and Photos 7 and 8).

The material exposed in the silt scarp adjacent to the jetty was clearly bedded, but the bedding planes had a distinct dome. It appears that the material was pumped as a slurry onto the beach area from the dredging area and that the dome in the bedding formed as a result of this method of dispersal. The material dries to quite a hard substance, but after rain or tidal inundation becomes softer. Runnels do not appear to develop in it after rain or wave action.

Erosion by waves only occurs when the tide level is sufficiently high and was observed during the period 3 April to 7 April 1989 (Photo 9) when the scarp was eroded by approximately 0.3m at pile 3 of the jetty.

When the tide level is sufficiently high for waves to attack the scarp at the edge of the spoil dump, silty material is released into the water and a silty plume is evident in the area of broken water around the spoil dump and at times extending approximately 80 to 100m out across the reef. In April 1989 the bulk of the silt appeared to be coming, not from the silt scarp, but from the rubble and silt scarp further from the jetty (Photo 10). A sample of silty water taken on 5 April 1989 yielded 260ppm suspended solids.

In the lower beach area below the silt scarp clean poorly sorted sand was overlain by grey and yellow silt and fine sand. It appears that this finer material was suspended by wave action at high tide and was able to settle as the tide level fell and consequently wave action diminished.

4.1.2 Subsurface Investigations of Spoil Dump

In order to ascertain the composition of the spoil dump various subsurface investigations were carried out. These comprised a combination of excavation by backhoe and augering.

A trial auger hole was put down at AH1, close to the silt scarp (See Figure 6 for location of hole). The results are reported later. It was only possible to penetrate 1.1m with the auger before inpenetratable coarse sand was encountered. Two further trial auger holes at AH2 and AH3 were attempted through sand and coral pieces, but very poor progress was made. Consequently it was decided that augering directly through the surface of the spoil dump was largely impossible owing to the nature of the surface layer. Some of the coral pieces encountered were larger than 0.3m across.

The first backhoe excavation was carried out at location C4. The excavation was 3.3m deep and penetrated the original beach material at 2.1m below the surface. A diagrammatic view of the section exposed is given in Figure 9. The original beach material (sample 31389/5) was much cleaner than that in the higher levels. That is, almost no silt or finer material was present (only 1%) and the material had bedding planes dipping seawards. The spoil dump material consisted of a surficial layer of approximately 1m of coarse sand with coral pieces and minor silt (samples 31389/4 and 31389/1). This overlaid a thin band, 0.12m, of horizontally bedded silt and sand which in turn overlaid a band of very contorted bedded silt (sample 31389/3). This material was either deposited in this curious conformation at the end of the pump line or was moved by bulldozer or similar action after initial settling and consolidation. This band of contorted silt in turn overlaid approximately 0.6m of horizontally bedded silt and fine sand (sample 31389/2). It therefore appears that this material settled naturally after having been pumped into the ponding area.

From this excavation it was learnt that the lower material in the spoil dump was deposited by pumping from the dredging area in the harbour. The end of the pipe was probably moved around in order to attain uniform deposition. Finally, coarse sand with coral pieces was pushed over the spoil dump to provide a robust level surface over which tractors and boat trailers could be driven.

As it appeared that the surficial metre of sand with coral pieces was the main problem encountered when augering, it was decided to excavate for approximately 1m by backhoe adjacent to hole C4 and then to find out if augering was a possibility. It was found in this hole that it was possible to auger for a total depth of 2.2m, that is for approximately 1.2m below the backhoe excavation. Very much less silt was found in this auger hole than was present in the hole excavated by backhoe despite the fact that they were only **1m apart**. This emphasised the **highly variable** nature of the material within the spoil dump, and that **any estimate of relative quantities of a given size fraction of material in the spoil dump can be only very approximate.**

Two further exploratory backhoe excavations were carried out at locations A4a and E4. These were both excavated to approximately 1m by backhoe and the remainder by auger. The results are presented later.

After these exploratory holes were excavated it was decided to carry out subsurface sampling according to a grid plan. The positions of the holes are shown on Figure 6.

The holes in rows A and B were excavated first as it seemed more important to know the composition of the material which was closer to the sea and more likely to be eroded. Then owing to constraints of time and weather only holes C1,C2, C3, C5 and holes D1 to D4 were excavated. Further holes in E row and C6 to C8 and D5 to D8 were not excavated as the material on the southern side of the spoil dump appeared to be coarser with a much lower percentage of silt. This is consistent with the known history of the spoil dump's construction. That is coarser material was heaped up around the edge of the present site of the spoil dump to form the settling pond with outlets close to the boat harbour. Subsequently, the outer part of the coarser material was bulldozed over the top of the pond to form the existing relatively impenetrable surface of the spoil dump.

4.1.3 Nature of Subsurface Materials

The detailed results from each of the auger hole sites or excavations has been recorded. Only selected information is presented in this report. In general considerably more silt was found in the northern holes than in the southern ones.

From a comparison of the backhoe/auger hole information and examination of the QNPWS photographs taken during the dredging operation it appears that a substantial proportion of the silt may be located near the landward end of the jetty. Unfortunately only a few holes were able to reach the original beach sand. The deepest beach sand level was 1.6m (L.W.D.) in hole BO. The beach sand was encountered at 3.0m elevation in hole B2 and 3.1m in the hole C4. In holes D1 and D3 it was around 3.5m. This information on original beach level, together with the photographic evidence, suggests that the deep pit excavated for the dredge spoil was in the vicinity of the landward end of the jetty. This was not appreciated while at Heron Island and consequently no holes were put down near the end of the jetty.

Figure 10 shows the test hole locations with the beach sand levels where known. Approximate contours for the original beach surface have been drawn. Computing volumes from these levels and using percentage silt estimates from the holes, it is estimated that approximately 10% of the spoil dump is silty material and that the major portion of this lies near the landward end of the jetty where the silt content has been estimated to be 65% in Auger Hole 1. Photographs taken by QNPWS personnel during the excavation for the saltwater intake trench confirm that there is a high silt content in this region of the spoil dump.

4.1.4. Quantity of Material in Spoil Dump.

The quantity of material contained in the spoil dump has been calculated relative to the shoreline as defined in the August 1984 survey for each of the four surveys made. In addition, it has been possible to use an aerial photograph (Photo 5) taken on 7 December 1987 to locate the seaward edge of the spoil dump and the top of the beach berm at that date. This information has been combined with survey data from May 1988 to give a representation of the spoil dump in December 1987 soon after its completion. Comparison with profiles at the northern end of the spoil dump near the jetty gives considerable confidence that the synthesised December 1987 spoil dump contours are correct but there were some questions about the profiles at the southern end of the spoil dump. However, these have now been resolved by additional field survey work locating coral features on the edge of the moat that can be identified in the photograph.

The volume changes are summarised in Table 2 and Figure 11. Initially there was about 14860m^3 of material in the spoil dump. This was reduced by 6% during the five months to May 1988 and by a further 6% during the following three years to June 1991. The seaward face of the spoil dump was significantly reshaped to a more natural beach profile but, except for silt, not much material may have actually been removed from the spoil dump onto the reef flat. Subsequently the overall rate of change has reduced and is only likely to accelerate if abnormal conditions such as those caused by a cyclonic or other severe wind event occur.

The question as to where this material has gone is not easily answered. Fine material, silt or clay sizes, will be dispersed and deposited on the reef flat, in the boat harbour or removed from the reef platform completely. This is discussed in section 4.4.4. However, it has been estimated that there is, on average, only 10% of silt in the spoil dump, although it is more concentrated towards the northern end near the jetty where there has been most erosion. Sand size material is most likely to have stayed on the beach, either forming the extended toe of the beach or possibly moving alongshore (see Section 4.3.2). Rubble either stays on the beach face or has been moved by human action to another location such as the base of the jetty or the seaward side of the helipad.

Some of the measured volume change may be more apparent than real since the erosion process tends to concentrate larger pieces of rubble on the beach face. The volume of such material, unless it forms a continuous shingle deposit, is not included in the calculated volumes. However this is unlikely to account for more than a few cubic metres.

Table 2 Quantity of Material in Spoil Dump

Date	Volume relative to August 1984 m^3	Volume change m^3	Volume change since Dec. 1987 m^3
7 Dec 1987	14860		0
		-940	
14-17 May 1988	13920		-940 (6%)
		-300	
1-5 April 1989	13620		-1240 (8%)
		-390	
3-5 Jan. 1990	13230		-1630 (11%)
		-150	
18-22 June 1991	13080		-1780 (12%)

4.2 Conditions Affecting Spoil Dump

4.2.1 Nature of Conditions affecting Spoil Dump

Erosion and release of silt from the spoil dump were expected to occur when waves broke upon its seaward beach face. Larger waves could be expected to cause a greater effect and the size of the waves is governed by the characteristics of the wind generating them and the water depth over the reef flat in front of the spoil dump. Hence it was anticipated that erosion and release of silt would be more likely to occur at high tide, when water depths over the reef are greatest, and with strong winds. The effect of the latter would depend upon their duration and also direction. It was also recognised that on some occasions wave heights would not be primarily determined by local wind conditions since swells generated by winds some distance away can cross the reef rim and break on the spoil dump beach. Another meteorological factor which might influence the release of silt is the rainfall.

Human activities such as excavations, reshaping of the beach face, relocation of rubble and the operation of boats may also cause the release of silt from or in the vicinity of the spoil dump. Major known disturbances occurred on 26 April 1989 when the excavation for the research station's new saltwater intake pipe was made, on 28 May 1989 when the beach face near the jetty was regraded and on 3 September 1989 when a similar operation was undertaken further south. Similar activities are likely to have occurred on other occasions but have not been recorded.

The observations of the various factors affecting the spoil dump are discussed in the following sections. Initially their relative influence is discussed using the data from the year May 1989 to April 1990 (section 4.2.2). Then the data from the two year period May 1989 to April 1991 is considered to determine variations and trends in the overall conditions affecting the spoil dump (section 4.2.3). The influence of wind speed and high tide levels upon the occurrence of silt plumes is specifically examined in section 4.2.4. This is followed by a discussion of a number of selected observed events, illustrating the way particular combinations of hydraulic and meteorological conditions produce, or do not produce, silt plumes (section 4.2.5). The results and discussion from these sections are reviewed in section 4.2.6.

4.2.2. Relative Influence of Various Factors

The relative influence during the year May 1989 to April 1990 of the various factors causing the release of silt from the spoil dump is shown on Figures 12 to 15. These figures give bar charts indicating the number of occurrences of silt plumes and no silt at station 2 for various magnitudes of wind speed, high tide level, rainfall and breaker height. As expected strong winds, higher high tides, intense rainfall and large waves are generally associated with silt plumes. The latter are much less common with light winds, lower high tides, dry conditions and small waves.

Since the waves are the primary agent eroding the spoil dump and causing the release of silt plumes and the waves are generated by wind, it is to be expected that the percentage occurrence of silt plumes should increase as both the wind speed and the wave height increase. Comparison of Figures 12 and 15 confirms this expectation. Table 3 quantifies this comparison. This table presents the percentage of time that the wind speed and the breaking wave height exceeded specified values during the period of observation, together with the percentage occurrence of silt plumes for the wind speeds or breaking wave heights greater than the specified values. For example, a silt plume was observed at station 2 on all but one occasion, when the wind speed exceeded 25kn, almost all occasions (86%) when it exceeded 20kn and most occasions (77%) when it exceeded 15kn. Similarly, silt plumes were observed on all occasions when the average breaker height exceeded 0.5m, almost all occasions (93%) when it exceeded 0.4m and most occasions (81%) when it exceeded 0.3m. For winds less than 10kn and waves smaller than 0.1 to 0.2m no silt plume was observed on most occasions (Figures 12 and 15).

Table 3. % Occurrence of Silt Plumes at Station 2 for Wind Speeds and Wave Heights greater than Specified Values May 1989 to April 1990

Wind speed, kn	≥0	≥5	≥10	≥15	≥20	≥25	≥30	≥35
% Exceedance of wind speed	99	85	62	29	10	2	0.3	0
% Occurrence of silt plumes	44	47	54	77	86	88	100	-
Av. breaker height at station 2, m	≥0	≥0.1	≥0.2	≥0.3	≥0.4	≥0.5	≥0.6	≥0.7
% Exceedance of breaker height	98	89	53	24	8	4	1	0.3
% Occurrence of silt plumes	44	48	62	81	93	100	100	100

With respect to tide level (Figure 13), silt plumes are present at station 2 on a majority of occasions when high tide level exceeds 2.6m and on most occasions when it exceeds 3.0m. Silt plumes only occur on a minority of occasions when high tide level is less than 2.2m. The influence of the tide upon the production of silt plumes is indirect. That is the higher tides allow larger waves to reach the beach and these larger waves break more vigorously, stir up more sediments, run further up the beach and are more likely to cut an erosion scarp than the smaller waves which occur at lower tide levels. The tide by itself does not create silt plumes. If there are no waves then it is most unlikely that even a very high tide will produce a silt plume. Figure 13 confirms that some of the highest tides were not accompanied by silt plumes.

Silt plumes are not as frequent at station 1 as at station 2, occurring only 25% of the time at the former site during the period May 1989 to April 1990 compared with 43% at the latter one (Figures 17 and 18). This is partly because waves greater than 0.4m are less frequent at station 1 than at station 2 (Figure 16) and partly because there is less silt present in that part of the spoil dump. Most silt plumes are relatively small and are confined to the shoreline. For example, 75% of the plumes observed at station 2 and 90% of those at station 1 were less than 10m wide.

The relationship between occurrence of silt plumes and rainfall during the 48 hour period preceding 0900h on the day of observation is shown on Figure 14. The chart indicates that silt plumes are more likely to occur when rainfall exceeds 10mm although there is an anomalous situation for rainfalls greater than 60mm. When the rainfall is less than 10mm but greater than zero, silty and nonsilty conditions are equally likely to occur. When there is no rain, no silt plume is the more likely condition but the number of occurrences of silt plumes is still significant. Clearly, while rainfall may have some influence on the formation of silt plumes, it is neither a simple one nor a dominant one.

In this regard it should be noted that, under normal conditions on a coral cay, rainfall percolates into the sand without any runoff. This is evidenced by the absence of runnels or other streamlike features. At low tide brackish water may percolate out onto the reef flat at the base of the beach. In the case of the spoil dump, silt lenses are present. These can impede infiltration, trapping small quantities of water above them. When these lenses are exposed by erosion some localised surface runoff may occur from such regions. Percolating streams may also entrain silt inside the spoil dump before discharging onto the reef flat at low tide.

Since observations were made close to high tide, the influence of reef-top tidal currents upon the movement of the silt plume at the time of observation is likely to be minimal, since there is very little change in water level at Heron Island during the half hour preceding and the half hour following high tide. Hence any observed movement of the plume is likely to be caused either by alongshore currents generated by the breaking waves or by wind-induced movement of the water on the reef flat. Directions of plume movement were observed at both stations 1 and 2 and water movement direction in the moat outside the breakpoint was recorded at station 1. In almost all cases plume movements were the same as the water movements. The direction of plume movement was generally consistent with that expected from the angle between the breaking wave crests and the shoreline. The occurrences of waves from various directions at each station are given on Figure 19. Referring to Figure 19, it can be seen that at station 1 waves between 110° and 200° will move silt plumes "westwards" or to the right when looking seaward, whereas waves between 200° and 290° will move the plumes "eastwards" or to the left. Most waves during this period would have moved plumes westwards from station 1 towards station 2. At station 2 the null movement direction is about 270° and waves from directions between 180° and 270° move plumes "northwards" or to the right, while waves between 270° and 360° move plumes "southwards" or to the left. At this location there are relatively more waves coming from the north compared with station 1, as would be expected, even though the majority of the waves still come across the southwestern reef flat.

Observational data for the second year, May 1990 to April 1991, supports the general conclusions concerning the influence of the various factors causing erosion of the spoil dump and release of silt plumes. Data equivalent to Figures 12 to 19 for the second year is given in Appendix B.

4.2.3 Overall Trends - May 1989 to April 1991

The overall trend in the occurrence of silt plumes during the period May 1989 to April 1991 is summarised for four month periods in Table 4. In general, up to the end of December 1990 silt plume occurrences had been decreasing, particularly at station 1. This applies to occurrences of both all plumes and large (>10m wide) plumes. This trend continues at both stations for large plumes up to the end of April 1991. Indeed since the beginning of September 1989 large plumes have been very rare at station 1, while at station 2 they have occurred on average 6 to 7 times every four months or once every 18 days. This is about one third the occurrence rate during May-August 1989. When all plumes are considered the same pattern of substantial reduction in frequency of occurrence is found at station 1. However, at station 2 the trend of decreasing plume occurrences is reversed during January-April 1991 when a significant increase occurred.

Table 4 % observations when silt plumes were recorded

Period	All Plumes		Plumes >10m wide	
	Station 1	Station 2	Station 1	Station 2
May-August 1989	31	54	7	20
Sept-Dec 1989	25	38	0	8
Jan-April 1990	19	38	1	5
May-August 1990	4	24	0.8	9
Sept-Dec 1990	9	21	0.8	5
Jan-April 1991	6	56	0	6

The variations in the conditions affecting the spoil dump and the occurrence of silt plumes during the period May 1989 to April 1991 are presented in two ways, firstly as monthly bar charts (Figures 20 to 24) and secondly in four monthly scatter plots (Figure 25).

Consideration of Figure 20 showing the monthly silt plume occurrences at stations 1 and 2 reveals considerable variations within the general trend given in Table 4. These variations reflect the interaction of the various factors causing silt plumes. Careful comparison of Figure 20 with Figures 21 to 24 will, in most instances, reveal the reasons for increased silt plume occurrences during a given month. For example, the windiest months are February 1989, March 1990 and February 1991. No plume occurrence observations are available for February 1989 but March 1990 and February 1991 were both months when silt plumes were observed at station 2 on more than 15 days. Winds were predominantly from the southeasterly sector during these months. In contrast waves were largest in May 1989 and September 1989. In both months silt plumes occurred at station 2 on more than 15 days. Significantly during May 1989 there was a greater proportion than normal of winds from the northeasterly sector and during September 1989 of northwesterly winds. These were the two months silt plumes were most frequent at station 1.

In considering the effects of tides upon the occurrence of silt plumes, it is important to recognise that observations are made only during the day time high tide. No observations are made at night. Consequently only half the potential silt plume-producing events are actually observed. Moreover, the effect of the diurnal inequality of the tides is to make the day time high tide higher than the night time high tide during January and February with the opposite effect occurring during June and July. Hence Figure 22 shows the variation of day time high tide levels with highest high tides during January and February and lowest high tides during June and July. Night time high tide levels will vary in the opposite sense. The significance of this can be seen by referring to conditions during June 1990. Day time high tides were low but night time ones were high. It was quite a windy month with persistent southeasterly conditions. Day time waves were generally small but this would not necessarily have been the case during the higher night time tides. Silt plumes were observed at station 2 on 13 days during this month but they were probably more frequent and more extensive during the night time tides.

As indicated above, highest day time tides occur during January and February. Silt plumes occurred on more than 15 days per month during January and February 1991 but not during the same months of 1990. Comparison with the monthly distributions of the various silt plume-producing factors does not suggest a simple answer for this although it appears that the increased rainfall during these months in 1991 may be significant. However, it was also recorded that there was a fresh exposure of silt following erosion of the beach in early January 1991. Consequently silt was again available for producing silt plumes.

While rainfall during both January and February 1991 was greater than 100mm, other months were considerably wetter. For example, rainfall exceeded 150mm during each month from February to May 1989 with two of them having falls of over 200mm. No silt plume observations are available for February and March 1989 but April and May 1989 were the two months when silt plumes were most frequent at station 2. Rainfall also exceeded 200mm during March 1990 during which month silt plumes were also very frequent. In contrast rainfall exceeded 600mm during April 1990 and this was the month with the lowest number of silt plumes during the period of observations, that is only three days at station 2 and none at station 1. As indicated in the previous section the influence of rainfall on the occurrence of silt plumes is not a simple one.

April and May 1989, the months with the largest numbers of silt plume observations, besides having high rainfalls, also had more occurrences of larger waves than normal. Furthermore there was significant disturbance of the spoil dump beach by human activities including the excavation of the trench for the research station's new saltwater intake (26 April 1989) and reshaping of the beach face and erosion scarp by earthmoving equipment (28 and 29 May 1989). Significant recession of the erosion scarp at the jetty occurred during early April (section 4.3.2), exposing a vertical face of compacted silt (Photo 6), which provided a source of silt to form silt plumes whenever waves or rain were able to erode it.

March 1990 was the windiest month during the period of observation with winds greater than 20kn on 50% of the days. There was a significant number of tides greater than 2.8m, although the distribution of day time high tide levels was probably similar to the annual distribution. Surprisingly the number of occasions when the breaker height exceeded 0.3m (Figure 24) was not as great as would be expected from the wind data (Figure 23). However, consideration of wind directions during March 1990 shows that there is a dominance of winds from directions between 80° and 120°, that is more or less along the long axis of Heron Island and its reef. Under these conditions the size of the waves reaching the spoil dump is smaller than would be expected for strong winds from more southerly or more northerly directions. However rainfall exceeded 200mm and the effects of the various causative factors was additive, producing silt plumes on most days.

In contrast during the following very wet month, April 1990, winds were generally below 15kn, waves were almost always below 0.3m and the number of tides greater than 2.8m was significantly less than during the preceding month (Figures 22 to 24). It was generally the calmest month during the period of observation. This fact combined with fewer high tides is clearly consistent with a small number of silt plumes. March 1989 had a similar distribution of high tides and relatively calm conditions but with less than a third the rainfall of April 1990. Unfortunately no information about silt plume occurrences is available for comparison. However, it seems probable that the rainfall had either little effect or a negative effect upon silt plume occurrences in April 1990. Thus it is possible that all available silt had been removed by wave action at higher high tides during the previous month and that there was little silt available to form silt plumes in April. The heavy rainfall presumably percolated into the spoil dump, concentrating loose silt particles at lower levels where they are less available for removal. The effect of rainfall upon silt plume formation appears to be largely dependent upon previous conditions which determine the amount of silt within the upper part of the spoil dump. It is probable that, unless there is major disturbance of the spoil dump by cyclonic waves or some large scale human activity, the effect of rainfall, if any, on the production of silt plumes will diminish as time proceeds.

4.2.4 Wind Speeds, High Tide Levels and Plume Occurrences

Given the fact that wave action at high tides is most likely to produce silt plumes and that the size of the waves generally increases with the speed of the wind generating them, an investigation was made of the wind speeds and high tide levels at which silt plumes occurred. One important reason for doing this is that wind speed data is available from HIAWS since 1980 and high tide levels can be predicted from tide tables for any period within the last decade or in the future. Hence if the availability of silt from the spoil dump remains the same or its variation is known, then it may be possible to hindcast the occurrence of silt plume events for the period November 1987 to March 1989 following reconstruction of the boat harbour but before the commencement of observations.

Figure 25 shows scatter plots of wind speed from HIAWS against predicted high tide level (DHM 1989, 1990) indicating when silt plumes occurred at station 2 and when there were no silt plumes. The plots have been compiled for four month periods, May to August 1989, September to December 1989 and January to April 1990. In each of these plots it is possible to define three areas. These areas are:

(i) lower high tides and/or lower wind speeds
- no silt plumes observed;

(ii) higher wind speeds at all high tide levels
- silt plumes always occur;

(iii) moderate wind speeds and all high tides except lowest ones
- either silt plumes or no silt plumes may be present.

Further consideration of the four monthly plots shows that the boundaries of these areas changed with time. In the first period May to August 1989 (Figure 25a), with two exceptions, silt plumes always occurred when the wind speed exceeded 15kn. With one exception no silt plumes were observed when the wind speed/high tide conditions lie below the line joining the points (W = 17kn, H.W. = 1.6m and W = 0, H.W. = 2.6m). During the second period September to December 1989 (Figure 25b), silt plumes generally occurred when the wind speed exceeded 17kn, although there were several cases when no silt plumes were observed at higher wind speeds. The lower limit for the occurrence of silt plumes also occurred at higher wind speeds and slightly higher tide levels than during the previous period.

In the third period January to April 1990 (Figure 25c), the wind speed above which silt plumes always occurred increased further, being about 20kn at the lower high tide levels. The lower limiting conditions for the occurrence of silt plumes did not change much but there were relatively fewer silt plumes occurring in the intermediate area compared with the previous period. Indeed, with only one or two exceptions, it can be stated that there were no silt plumes during the period September-December 1989 when the wind speed was less than 10kn and the high tide level was less than 2.6m. In the following January to April 1990 period these limits had risen to 16kn and 2.7m.

An analysis of the various silt plume occurrences which do not fit into the above limits, that is either the wind speeds or high tide levels at which plumes occur are low, shows that in most cases at least one of the following situations occurred:

(i) human activity, such as a boat, beach reshaping or previous excavation, had produced the plume;

(ii) swells, either following windy events or from distant storms and often with longer periods than usual, had eroded the silt scarp;

(iii) rain had caused the plumes.

Furthermore, it was found that, when no silt plumes were observed for relatively high wind speeds and high tide levels, in most cases one of the following situations existed:

(i) atmospheric conditions, e.g. overcast sky, late afternoon, poor visibility may have resulted in plumes not being detected;

(ii) wind direction was one which does not produce waves large enough to erode the spoil dump, e.g. easterly to eastsoutheasterly winds blowing along the long axis of Heron Island and its reef or southsouthwesterly to westerly winds for which Heron Reef is sheltered by Wistari Reef.

The preceding results indicate that silt plumes were becoming less frequent and were occurring at higher wind speeds and higher high tide levels than had been the case earlier. Not only did plumes become less frequent than they were in mid 1989 but those that did occur were generally less extensive (Table 4). Moreover larger plumes (ƒ 10m) occurred at increasing wind speeds and higher tide levels. In May-August 1989 the lower bounds for the occurrence of such plumes were W = 15kn and H.W. = 2.35m, these had extended to possibly 20kn and 2.55m during September-December 1989 and during January-April 1990 plumes ƒ 10m were only observed at high tide levels greater than 2.75m.

The pattern of decreasing silt plume occurrence has continued until the end of 1990 as has already been recorded in Table 4. During May to August 1990 most plumes were either caused or accompanied by rain while during September to December 1990 few plumes were associated with rain. As stated in section 4.2.3 (Table 4) silt plumes, albeit small ones, became much more frequent again during January to April 1991.

The reasons for the recent increases in silt plume occurrences will become apparent after consideration of specific silt-producing events in section 4.2.5.

4.2.5 Specific Silt-producing Events

The preceding analysis has been based upon the number of occasions when silt plumes were observed. One observation was made just before each day time high tide. However the responses represented by these observations are not completely independent of one another since the meteorological events causing them may extend over several tides or days. In each event the varying wind speeds generate waves of varying heights. At low tide no waves reach the spoil dump since all waves generated outside the reef will break on the reef rim. As the tide rises waves will begin to pass over the reef rim and travel across the reef flat to the spoil dump. Few specific observations are available but the general impression is that little wave action reaches the spoil dump until the tide level exceeds mean sea level which is 1.6m. This is largely because the water depths are still quite small, i.e. about 0.6 to 0.8m, since the controlling levels of the reef flat are about 0.8 to 1.0m. For the more severe events, the waves reaching the beach increase in height relatively rapidly as the tide approaches high tide level and the maximum possible size of the waves is limited by the water depth over the reef flat and hence by the height of the high tide. Hence the larger waves are more likely to occur at higher high tides. As the tide falls the process is reversed. This variation of wave height with tide height is shown schematically in Figure 26a.

Confirmation of the limiting effect of the tide upon wave heights was obtained by plotting both average and maximum breaker heights against tide level. Assuming a reef rim/flat level at about 1.0m, it was found that the maximum breaking wave height was in virtually all cases not greater than 0.6 times the water depth and the average wave height was not greater than 0.4 times the water depth. If the observed average wave height is equated with the significant wave height used in coastal engineering practice (CERC 1984, p3-2), the above limiting ratios are consistent with those observed in either laboratory experiments on very flat slopes (Nelson 1985) or in the field at John Brewer Reef (Hardy et al. 1991a & b).

Other factors will influence the wave conditions on the spoil dump beach. Large waves breaking on the reef rim will increase the water level on the reef flat above that due to the tide (Figure 26b). However, this wave set-up is greatest at lower tide levels and reduces as the water depth over the reef increases (Gourlay 1991c). It is more likely to modify current circulation patterns on the reef than to produce large changes in wave height. Nevertheless any significant currents on the reef flat will cause changes in waves by refraction. These changes may in turn cause changes in wave height and wave direction at the beach.

Wind blowing over the water on the reef flat will generate both currents and waves. The wind-generated currents will modify the tidal currents and the locally generated wind waves will be superimposed upon the waves coming over the reef rim. On many occasions, probably a majority of occasions, the waves observed on the spoil dump beach were short, steep, wind waves generated locally on the reef flat. Their periods are generally between 1 and 2s. Such waves may not have attained their maximum depth-limited height. On other occasions the waves had clearly come from outside the reef, having first broken on the reef rim. On a few occasions waves were identified which had passed over the reef rim without breaking there. Wave periods of these waves are generally at least 4 to 5s, or somewhat longer. The periods of reef-top waves are generally less than those of the offreef waves (Gourlay 1991c). On many occasions two and sometimes more wave trains were observed on the beach. These would normally be wind waves locally generated on the reef flat and ocean waves coming over the reef rim from one or other or both sides of the reef.

To investigate the nature of events which may have influenced conditions on the spoil dump a table was compiled of all observations when one or more of the following conditions occurred:

silt plume width	≥10m
average breaking wave height	≥0.4m
wind speed (HIAWS)	≥20 kn
24 hour rainfall to 0900h	≥10mm

This data is reproduced in Appendix C and includes, besides the quantities listed above, breaking wave direction, wind direction (HIAWS) and predicted high tide level. From this table a number of events during the twelve month period up to April 1990 were selected as being, in one way or another, either significant or typical of certain conditions. The events follow one another in chronological order and are numbered E1 to E8. Subsequently after the acquisition of a further 12 months data, three further events E9 to E11 were selected from the latter period together with another one EO prior to the earlier period.

The time series for each event is reproduced in figures 27 to 38. Each figure is divided into four parts. The upper part shows the predicted tide at Heron Island as a continuous line plotted to the local low water datum. The average breaker height and the silt plume width are plotted as discrete points with their scale zeros at 1.0m tide elevation, i.e. the approximate elevation of the reef flat. Hence it can be assumed that wave heights and plume widths were zero during the times the tide level is below 1.0m. The maximum silt plume width has been set at 50m although in a few cases the plume extended further and in one case to the reef edge (300m). This part of the graph emphasises the pulselike character of the disturbance applied to the spoil dump. Twice a day waves are able to attack the beach for a few hours at a time. Any silt plume produced will tend to move away from the spoil dump with the ebb tide. In most cases the silty water may drain over the reef flat south of the wreck or out through the boat harbour. In other cases it may be ponded on the reef. During this process silt will tend to settle out, particularly as the water level drops below mean tide level and the waves die away. Silt deposited on the reef flat may be resuspended by waves during the following high tides. So each tidal pulse of wave action may have some influence upon the plume conditions during the next one. It should be noted that only half the total number of silt-producing events are actually observed. There are no observations during night time high tides.

The second and third parts of each figure show the three hourly wind speeds and directions plotted as a continuous line. It should be noted that wind velocities are sometimes greater than those recorded in Appendix C since the latter are the values recorded closest to the time of observations. The fourth part shows the rainfall recorded over the twentyfour hour period prior to 0900h each day. Only the total has been extracted from the Bureau of Meteorology record sheets, so it is plotted as though it occurred at a uniform rate during each day. In the discussion of each event use has been made of all data obtained, not just that recorded on figures 27 to 38 or in Appendix C.

The conditions occurring during each of the twelve selected events are summarised in Table 5. A detailed discussion of events E1 to E8 is given in Appendix D.

The selected events illustrate the diversity of conditions causing erosion of the spoil dump and the release of silt plumes.

- Event E3 produced the largest observed waves which stirred up reef flat sediments and eroded the spoil dump to produce the most extensive silt plumes observed during the monitoring period.

- Events E2 and E7 represent fairly typical silt producing events involving winds from the southeastern sector at mean high spring tides and without any rain.

- Events E4 and E10 show the action of onshore winds from the northwest in producing erosion and narrow silt plumes.

- Events E5 and E6 show the influence of tide level in determining whether or not offshore (E to ESE) winds produce a silt plume.

- Event E9 is an example of conditions when large waves broke on the reef rim but the waves reaching the spoil dump were only able to cause erosion during the higher night time tides.

- Event E1 represents a situation where the combined effects of maximum depth-limited waves at mean spring high tides, rainfall, and disturbance of the beach face and erosion scarp by earthmoving equipment produced a very turbid silt plume.

- Event E8 was the longest observed sustained windy event, during which tides varied from high spring tides to low neap tides. At the beginning of the event reef flat sediments were stirred up while near its end heavy rainfall produced streaky silt plumes originating from the spoil dump.

- Events EO and E11 both involved swells from distant cyclones in the northwestern Coral Sea. Local winds were not significant in generating the waves which reached the spoil dump. The swell waves crossed the northern reef rim and broke on the spoil dump near the jetty at very high tides (3 to 3.5m). In both cases significant erosion of the spoil dump occurred and a silt scarp was exposed. This newly exposed silt scarp then became the source of an increased number of silt plume occurrences during the succeeding period.

4.2.6 Review of Conditions producing Silt Plumes

The primary cause of silt plumes is waves breaking on the seaward face of the spoil dump at high tide. Waves with average breaker heights ƒ 0.4m almost always erode the spoil dump, producing silt plumes (Table 3). Often these larger waves also stir up reef flat sediments producing general turbidity. The waves reaching the spoil dump are of three types:

(i) wind waves locally generated on the reef flat;

(ii) wind waves generated off the reef;

(iii) swells generated some considerable distance from the reef.

On many occasions, particularly with east to southeasterly weather, waves may come simultaneously from both the northern and southern sides of the reef.

High tides by themselves do not create silt plumes. However, by controlling the water depth over the reef flat, the tide level limits the height of the waves reaching the spoil dump. At higher high tides, larger and longer waves run further up the beach face and are more likely to erode it.

As waves are generated by wind, the occurrence of silt plumes is also linked with wind speed, that is plumes increase in frequency as the wind speed increases (Table 3).

However, other factors may produce silt plumes when wind speeds are not very strong. Swell from distant cyclones coming across the reef edge on very high tides can, and did on two occasions, cause significant erosion of the spoil dump accompanied by silt plumes. These two events in early April 1989 and early January 1991 exposed fresh silt scarps, initiating new cycles of silt plume production.

Rain and human activities, such as boat movements, excavations, etc., may also produce silt plumes when wind speeds are not strong enough to generate sufficiently large waves or when tide levels are too low to allow large waves to reach the spoil dump.

On some occasions, when winds were strong (> 20kn), no plumes were recorded. Such conditions were usually associated either with bad atmospheric conditions, e.g. rain, which may have prevented the observation of a silt plume or with certain wind directions, east to eastsoutheast or southsouthwest to west for which the spoil dump is partially sheltered and hence exposed to somewhat lower wave heights.

Plume widths are generally narrower with onshore (northwesterly) winds than with southeasterly winds.

Silt plumes at high tide generally moved in the direction of the alongshore current generated by breaking waves and wind stress. At the lower tide levels before and after high tide the plume movement direction would be increasingly determined by tidal current directions.

In general, the frequency of occurrence of silt plumes decreased from April 1989 to April 1991, particularly at station 1 at the eastern end of the spoil dump. However, there was an increase in silt plumes at station 2, just south of the jetty, during January to April 1991 (Table 4) following the exposure of a fresh silt scarp in early January 1991.

Plumes were less frequent at station 1 (25%) than at station 2 (43%). This reflects the relatively greater frequency of occurrence of larger waves at station 2 and particularly the greater availability of silt at that site.

Table 5. Significant Silt-Producing Events at Heron Island April 1989 to April 1991

EO	29 Mar. to 7 Apr. 1989	Swells originating from tropical cyclone "Aivu", ENE of Townsville, came across northern reef edge when HW ≈ 3m. Significant erosion of spoil dump near jetty and exposure of silt scarp.
E1	24 May to 1 June 1989	SE winds 20 to 30kn with "monster waves breaking on [the reef] crest" on 29 May. HW = 2.3 to 2.5m. Maximum depth-limited waves at spoil dump.Reshaping of beach face and erosion scarp by earthmoving equipment on 28 May. Very turbid silt plume on 29 May.
E2	25 to 29 July 1989	SSE to SE winds > 20kn. Daytime HW ≈ 2.5m. Wide silt plume 15 to 30m extending behind boat harbour. No rain.
E3	17 to 21 Aug. 1989	SE winds to 30kn. HW = 2.7 to 3.0m. Maximum depth-limited waves -largest observed. Extensive silt plume extending over entire reef flat includes sediment stirred up directly from reef flat. Erosion at jetty (station 2) on 19 Aug.
E4	17 to 21 Sept 1989	NNW (onshore) winds 15 to 20kn. HW ≈ 2.8m. Erosion of scarp near jetty. Narrow (2 to 4m) silt plume.
E5	19 to 22 Nov. 1989	ESE winds 25 to 30kn. HW ≤ 2.4m. Waves breaking on reef rim. Small waves at spoil dump. No silt plume. Offshore wind event not producing a silt plume because of low HW level.
E6	27 to 30 Nov. 1989	E winds 15 to 20kn. HW ≈ 2.8m. Small waves, silt plume. Offshore wind event producing silt plume because of high HW level.
E7	29 Jan to 2 Feb 1990	ESE winds > 20kn. HW 2.6 to 2.8m. No rain. Silt plume extending behind boat harbour.
E8	11 to 30 Mar 1990	Longest sustained windy event recorded. SE to SSE winds gradually shifting E to NE. 30kn on 13 Mar - generally 15 to 20kn until 27 Mar. Waves initially from southern side of reef with maximum depth-limited waves at spoil dump. On 13 Mar. "whole reef [was] turbid and milky" and on 14 Mar. big rocks were moving on beach. HW 3.0m to 1.7m to ≥ 3.0m. Heavy rain 26 to 29 Mar. produced streaky silt plumes.
E9	7 to 11 June 1990	SE winds to 32kn. Large waves breaking on both northern and southern reef edges. Higher HW (2.7m) at night, lower daytime HW (2.2m). Observed waves did not reach scarp but erosion recorded - must have occurred during higher tides at night.
E10	14 to 18 Aug. 1990	NW (onshore) winds to 28kn on 18 Aug. "seas furious" at reef edge - "harbour in tumult" - waves breaking across reef flat causing turbidity on 15 Aug. HW ≈ 2.5m, scarp erosion with narrow silt plume.
E11	1 to 5 Jan. 1991	Swells associated with tropical cyclone "Joy" coming over northern reef edge. E to NNE winds < 20kn. Very high tides ≈ 3.5m (may include some wave set-up). Substantial erosion of scarp near jetty during daytime high tides.

4.3 Changes in Spoil Dump Shoreline

4.3.1. Shoreline changes before September 1987.

Changes in the shoreline position at the western end of Heron Island have been recorded during the last 30 years (Flood 1974, 1981, 1984, Gourlay-unpublished). For a coral cay the shoreline is most conveniently defined by the edge of the sand deposit forming the cay, where the beach face intersects the reef flat (Figure 39, inset). During the last decade since cyclone "Simon" in February 1980, there have been no significant cyclonic events which have affected the island and the shoreline behind the boat harbour has been relatively stable compared with the 1960s and early 1970s (Figure 39).

The sand spit stayed south of the boat harbour with some seasonal movement of sand northwards to the region behind the boat harbour near the helipad. There was a continuing movement of the sand spit eastwards covering more and more of the western end of the beachrock outcrop on the southern side of the island. Fluctuations in the position of the edge of sand at the bottom of the beach, in the direction normal to the shoreline were of the order of 5 to 15m. In March 1987 the beach in the vicinity of the jetty site was about 5m landward of its August 1984 position and the most southerly portion of the sand spit was 15m seaward of its August 1984 position. There have been no signs during the last decade of the sand spit returning to its northwestern location of the 1950s and 1960s.

The last recorded position of the shoreline (March 1987) before the construction of the boat harbour may represent a somewhat extreme condition since it precedes the southeasterly trade wind season and could be expected to reflect the greater frequency of more northerly winds that generally occur during the latter part of the preceding year and through the summer months. It also follows a year (1986) in which a moderate ENSO event occurred and during which the annual resultant wind energy direction was more easterly than it had been in the two preceding years (1983-84) and the following year (1987) (Flood 1991).

4.3.2 Shoreline Changes since Spoil Dump Formation

The seaward face of the spoil dump has changed since its initial formation. This is primarily a result of wave action, particularly at higher tide levels (section 4.2). It is also affected by human activities, primarily the reshaping of the beach face using earthmoving equipment and the consequent redistribution of beach material, particularly rubble.

The overall change in shoreline resulting from the spoil dump is shown in Figure 40 in which the plan outlines of the shoreline are shown for March 1987 and May 1988. It can be seen that, at a point about 30m south of the jetty, the base of the spoil dump beach was about 35m seaward of the previous shoreline in March 1987. The spoil dump extended about 130m from the southern side of the jetty to where it intersected the previous shoreline.

Since the formation of the spoil dump, its shape has changed as it has been reshaped by waves. The change in volume per metre is given on Figure 41, which also gives the location of the profiles used in the calculations. Figure 41 shows that the northern part of the spoil dump has steadily lost material between December 1987 and June 1991. In contrast the southern part of the spoil dump initially lost material between December 1987 and May 1988. There was then little further loss between May 1988 and January 1990 but subsequently the southern part of the spoil dump gained material between January 1990 and June 1991.

Consideration of the changes in shape along each profile used for the volume calculations (Figures 42 and 43) shows that there has also been redistribution of sediment along profiles.

This is particularly so for profiles 3 and 4 south of the jetty where the upper part of the beach has been eroded and the lower part has extended seaward onto the reef flat. Similar behaviour is recorded at profiles 6, 7 and 8. Losses from the upper beach on profiles 3 and 4 between December 1987 and April 1989 are largely due to erosion by waves although there is evidence of some possible mechanical reshaping of the upper part of the seaward edge of the spoil dump at profile 3. On the other hand, losses from the upper beach from these two profiles between April 1989 and January 1990 have been significantly affected by reshaping operations during late May 1989. Reshaping of the central portion of the upper beach occurred during early September 1989. At the southern end of the spoil dump the losses from the upper part of the beach at profiles 7 and 8 between early May 1988 and April 1989 could also have been affected by reshaping operations in mid May 1988. However there is also reason to believe that wave-induced erosion occurred on this part of the spoil dump in November and December 1988 (Photo 7).

Profile changes have been surveyed along both sides of the jetty with levels being taken at each pile and in between where appropriate (Figure 44). This is the part of the spoil dump shoreline most subject to erosion since waves coming from the northern side of the reef are refracted onto this part of the beach. Shoreline recession was initially very rapid at the jetty but has slowed significantly since April 1989, particularly on the southern side of the jetty. This reduced rate of erosion could be a result of both fewer erosion-producing events and the protective action of rubble placed under and adjacent to the jetty in late May 1989 and probably other occasions, e.g. early September 1989.

A further profile along the southern side of the jetty was recorded in August 1990 by measurements made from the known deck level of the jetty. It showed little recession of the scarp since January 1990 but a lowering of beach levels in front of it. Such behaviour is consistent with the accumulation and placement of rubble in front of the scarp to form a seawall. Further recession of the scarp occurred between August 1990 and June 1991.

Observations of the position of the erosion scarp on the southern side of the jetty were recorded daily. A plot of these observations, together with other data obtained from aerial photographs and spoil dump surveys, shows a continuing recession of the beach crest at the jetty (Figure 45). Significant erosion (3 to 5m) occurred on (an) undefined occasion(s) between May and August 1988, and in early April 1989. The beach crest was rebuilt seawards during late May 1989 by mechanical means but the fill resulting from this operation had largely gone by September 1989 when the beach crest had returned to the same position it had during early May 1989. During the 15 month period from September 1989 to December 1990 a further gradual recession of 2m occurred. During the first week of January 1991, 3m recession of the beach crest occurred during very high tides. This was followed by almost as much accretion during March 1991 as strong eastsoutheasterly winds blew sand from the beach and the top of the spoil dump back onto the beach face in front of the scarp at the jetty.

Investigation of the two significant erosion events for which observations are available reveals a common pattern - the occurrence of high to very high high tides (3.0 to 3.2m predicted height) and longer period swell waves coming from the northern side of the reef. In both cases the swells were associated with the presence of cyclones off the northern Queensland coast, in April 1989 cyclone "Aivu", and in January 1991 cyclone "Joy".

The two occasions during 1989 when mechanically placed fill was eroded were associated with different meteorological conditions although the hydraulic conditions were similar to the other erosion-producing events. On 30 June 1989, 20kn southeasterly winds had produced 6 second waves coming over the northern edge of the reef when the high tide was 2.9m. On 18 September 1989, 15 to 20kn northwesterly winds generated 4.4s waves from the northwest when the high tide was 2.8m. In all cases observed average breaking wave heights at station 2 were at least 0.4m.

Since the spoil dump was formed there have been noticeable changes to the beach east of it opposite the research station. These changes have been recorded on aerial photographs taken by QNPWS personnel and, because both buildings and beach rock outcrops are visible in the photographs, it has been possible to measure relative changes in the shoreline position at two sections (Figure 46) - one, AA, near the western end of the exposed beach rock, a little westward of Flood's station T and the other, BB, behind the beach rock, approximately at the same location as Flood's station U (See Figure 49 for location of Flood's stations). The movement of the seaward edge of the sand at each section is shown in Figure 46a. Unfortunately no suitable photos exist between December 1987 and early September 1988, during which period the beach at section AA nearer the spoil dump accreted while that at section BB eroded. In early November 1988 a strong wind event occurred and the beach at section BB receded further to a position 6m landward of its December 1987 position. This was accompanied by a significant accretion further along the beach towards the spoil dump at section AA. In early December 1988 the beach at section AA had accreted 10m since the formation of the spoil dump. By January 1989 the more extreme effects of the November 1988 event had disappeared. The beach at section AA had receded again by about 2.5m while that at section BB had accreted. During 1989 these trends continued, although not uniformly at each section, until in January 1990 the beach at section AA was only about 2m further seaward of its December 1987 position while at section BB it had returned to its position at that time.

4.3.3. Synthesis of Beach Sediment Movements since December 1987

From the observations recorded in the preceding section it has been possible to deduce the general littoral sediment movements which have occurred as the spoil dump has been reshaped by prevailing winds, waves and tides assisted by human actions from time to time. The resulting synthesis which is summarised in Figure 47 is provisional in the sense that it might be amended if further information were available and if further detailed analysis of wave and other conditions recorded at the spoil dump since December 1988 were made.

During the period immediately following the formation of the spoil dump - December 1987 to May 1988, both the northern and southern sections of the spoil dump were eroded. The northern section in the vicinity of the jetty is generally attacked by waves coming from the north while the southern section is attacked by waves coming up Wistari Channel and over the reef edge south of the boat harbour. The erosion occurred on the upper part of the spoil dump as waves cut an erosion scarp and reshaped the seaward face of the spoil dump to form a more natural beach. Sand and shingle was mostly moved seaward to extend the base of the beach onto the reef flat or into the moat on the landward edge of the reef flat. Rubble was generally left on the beach in the vicinity of the erosion scarp at the uprush limit for the larger waves. Silt would have been suspended and mostly removed offshore or alongshore by tidal and wind-induced currents. The amount of beach reshaping and redistribution of rubble by human activity during this period is unknown but may have been significant.

Between May 1988 and April 1989 erosion of the upper beach, both near the jetty and at the southern end of the spoil dump, continued. During this period the movement of sand and shingle tended to be alongshore rather than offshore. The base of the beach on the central part of the spoil dump moved seaward and the beach eastward of the spoil dump accreted as sand covered the western end of the beach rock. It is probable that the net alongshore movement of sand was to the south and east during this period as there is little evidence of sand accreting to the north of the jetty. A temporary reversal of this process took place in November 1988 when sand eroded at station U was apparently moved westward to station T. It is probable also that southeasterly weather between May and August 1988 also moved sand westwards from behind the beach rock to cause accretion of the beach behind the western end of the beach rock.

Since April 1989 the face of the spoil dump beach has become increasingly depleted of sand and armoured with shingle. The sand supply southward has reduced and the edge of the sand on the eastern portion of the spoil dump has receded so that by January 1990 the beach in this region was in much the same position as it was in December 1987 just after formation of the spoil dump.

Overall the spoil dump shoreline is attempting to realign itself to be in equilibrium with the waves reaching it from the northern and southwestern sides of the reef (Figure 48). Waves from the east are refracted at the northern reef edge, travel across the reef flat, and are refracted again as they cross the boat harbour. They approach the timber seawall protecting the helipad and the spoil dump shore south of it from a generally northwest to northnorthwesterly direction, being reflected from the seawall and breaking at an angle to the spoil dump shoreline. The shoreline response is to realign itself in the wellknown crenulate bay shape associated with sandy shorelines downdrift of headlands or seawalls (Silvester 1974, p75, 144). Such behaviour occurred twenty years earlier following completion of the rock seawall protecting the resort buildings on the northwestern side of the island. After the helipad was constructed in 1968, it was endangered by erosion in 1970 caused by waves coming largely from the north (DHM 1970-1972). The subsequent construction of the timber seawall in 1971 and its reinforcement with concrete blocks since that time has simply transferred the erosion-prone zone to the region south of the helipad in the vicinity of the jetty. Similar realignment of the shoreline and transfer of the erosion-prone zone along the western end of a coral cay has occurred during recent years at Green Island. On that island southeasterly waves have eroded and realigned the beach north of the revetment protecting the base of the jetty.

At Heron Island this realignment of the shoreline puts maximum attack on the beach in the vicinity of the jetty. The situation is exacerbated by waves coming from the southern side of the reef also breaking on this part of the shoreline. This has caused concern and rubble exposed on the beach further south has been relocated to protect the jetty. Consequently this portion of the spoil dump shoreline is unlikely to assume a natural stable beach form. Indeed the probable absence of a significant supply of sand from the north along the seawall means that some form of protection of the spoil dump shoreline near the jetty is indeed necessary.

The southern portion of the spoil dump and the beach to the east of it opposite the research station has generally realigned itself to be parallel with the crests of waves crossing the southern side of the reef. These waves travel up Wistari Channel, are refracted at the reef edge and then travel across the reef flat, approaching the spoil dump from the southsouthwest. A refraction analysis undertaken independently of this project suggests that this process is very sensitive to wave period but, if conditions are right, significant wave energy will reach the beach westward from about station U with a direction parallel to the present shoreline alignment between there and the central part of the spoil dump. At the northern end of the spoil dump these waves are further refracted by the boat harbour and they also at times may break on the spoil dump in the vicinity of the jetty.

From the work done for this project and from other sources the following significant factors need to be considered in relation to the stability of the spoil dump and the western end of Heron Island generally.

(i) Climatic variation is causing continuous changes in the resultant energy vector of the wind which generates the waves reaching the island (Gourlay 1983a, Flood 1986, 1991). Changes in wind direction, particularly during the 1970's, would have increased the relative frequency and intensity of waves approaching the western end of the island from the northern reef edge. The erosion of the western end of the northern beach and the removal of dredge spoil deposited in front of the seawall in late 1972 is consistent with the observed shift of wind direction to the east during the 1970s. The reported more southerly winds during the 1980s (Flood 1991) did not result in any movement of the sand spit towards the north.

(ii) Cyclonic waves are very significant in causing changes to the cay shoreline. For example, the erosion and southerly movement of the sand spit which required the construction of the rock seawall on the northwestern side of the island was initiated by cyclone(s) in the mid-1950s. A cyclone or a series of cyclones may initiate a change which lasts several years before a new stable situation develops (Gourlay 1988).

(iii) Wave action reaching the western end of the island is significantly influenced by the shape of the reef and the proximity of other reefs, in this case Wistari Reef. Preliminary work for another project suggests that the waves reaching the spoil dump and the western end of the island around the southern side of the reef are very significantly modified by refraction as they travel up Wistari Channel. This results both in a substantial reduction in their height and a dispersion of wave periods with the longer period swells breaking on the reef rim further to the south and only waves of average period (e.g. about 6s) crossing the reef opposite the spoil dump. Consequently the dominant southeasterly conditions in the ocean east of the reef are not necessarily repeated at the western end of the island. The western end of the island is also clearly protected by Wistari reef from waves coming from the southwesterly sector.

(iv) Engineering works, including the boat harbour, various walls on the reef flat and along the island's shore, and the spoil dump itself, all have an influence upon the conditions affecting the stability of the island's western beaches. Indeed it is probable that they now determine the shoreline position under normal conditions and unless destroyed or substantially modified by either cyclonic waves and surge or human actions will continue to do so for several decades.

In the light of the above factors it could be speculated that the natural equilibrium position of the leeside sand spit on Heron Island was not always on the northwestern side of the island as would be generally expected for islands and reefs aligned in an east-west or eastsoutheast - westnorthwest direction in a wave climate dominated by southeasterly winds and swells. Because of its unique topographical conditions it is possible that, under certain conditions, the spit was stable in the southwesterly location, that is where the spoil dump is now located. Movement from one position to the other may have required the impact of cyclonic conditions to provide the impulse for the change.

4.4 Nature of Sediments Released from Spoil Dump

4.4.1 General Considerations

The investigation of the subsurface levels of the spoil dump confirmed what was clearly visible on its surface, that is, all classes of sediment from rubble to silt, but excluding clay-sized material, are present in varying proportions at each location. The question now to be addressed is how this heterogeneous material will be sorted and redistributed as waves erode the seaward face of the spoil dump. In the following discussion attention is focussed upon the more mobile sand and silt fractions since sand is the principal material found naturally on the cay's beaches and silt is the material causing significant environmental concern. Under normal conditions, similar to those observed during the monitoring period, there is no evidence that coarser material, such as shingle and rubble, is being removed from the spoil dump by wave action either offshore into the moat or the boat harbour or onto the reef flat, or alongshore to adjoining beaches. Coarse material may be significantly redistributed during cyclonic or other extreme wave events but these have not occurred since the spoil dump was formed. Under present conditions their relocation by human action is a much more likely occurrence.

The sorting and redistribution of silt and sand from the spoil dump will be discussed under the following three headings.

(i) Natural beach sediments on Heron Island.

(ii) Sediments on spoil dump beach and in its vicinity.

(iii) Silt in spoil dump, plumes and reef flat deposits.

Undisturbed beach sediments from other locations on the island provide a reference condition with which the spoil dump beach sediments may be compared. It is to be expected that, as the spoil dump beach sediments are sorted and redistributed by normal beach processes, they will gradually attain grain size distributions similar to those of natural beach sediments. The finer material will be removed, as the waves rework the heterogeneous material stored in the spoil dump, but the coarse rubbly material will be left on the beach face. The presence of this coarse material may impede the attainment of a "natural" grading by the beach face sediments.

Summary data of all sediment samples used in the discussion of sediment released from the spoil dump (sections 4.4.2 to 4.4.4) is recorded in Appendix E. Grain size distributions are presented only for selected samples explicitly referred to in the text. For convenience these figures are presented in Appendix F, being referred to in the text as Figures F1, F2, etc. The locations of various samples are shown on figures 49, 50 and 51.

4.4.2. Natural Beach Sediments on Heron Island

Several beach sand samples have been collected during visits to Heron Island prior to the construction of the spoil dump in 1987. They are included in the list of natural beach sediment samples in Appendix E. These samples give some idea of the characteristics of the natural beach sediments but they are limited in number and are not necessarily completely representative of the cay's beach sediments.

On the eastern end of the island, the beach sediment samples contained negligible amounts of material finer than 0.18m (2.5ϕ). The sand was generally finer at the top of the beach and became coarser down the beach. Median sizes ranged from around 0.3 to 0.4mm (1.5ϕ) at the top to 0.6 to 1.5mm (1 to - 1ϕ) on the lower beach. Comparison of a surface and subsurface sample in front of an erosion scarp between stations C and D (Figure 49) showed that the finer sand (d_{50} = 0.3mm) had been recently deposited over coarser material (d_{50} = 0.65mm)(Figure F1). This shows that whilst there is considerable variability in the natural grain size distributions of cay beach sands, there is virtually never any material finer than 0.18mm (2.5ϕ) present.

On the southwestern spit in the vicinity of Flood's stations R and S at the subsequent location of the spoil dump, there was a wider size range of particles present. On the upper beach no material finer than 0.125mm (3ϕ) was found, while on the lower beach there was nothing finer than 0.5mm (1ϕ). The median size of the sand on the upper beach near the berm crest was 0.3mm and this increased down beach to 0.6mm just above the higher high water swash deposit. Again the sand became coarser further down the beach face with d_{50} = 1.3mm just above the edge of the beach sand. The lower intertidal portion of the beach was generally covered with poorly sorted coarse pieces of coral and coral rubble, some pieces as large as 100mm. Coral debris also tends to accumulate at the run-up limits for both the higher and lower high tide levels.

Further samples were collected from the southern beach after the construction of the spoil dump. Six samples were taken along a profile a little to the east of Flood's station W in May 1988. They show a variation in size from d_{50} = 0.75mm, with nothing finer than 0.25mm, (W1) in the trough behind the beach rock to d_{50} = 0.4 to 0.6mm, nothing finer than 0.125mm, on the upper part of the beach. Two more samples were collected in April 1989, 04489/2 from above the beach rock at the eastern end of the island and 05489/8 from above the western end of the beach rock near the spoil dump (Figure F2). Both were collected from below high tide level and are generally well sorted with median sizes of 0.9 and 1.2mm, and virtually no material finer than 0.5mm (1ϕ). A sample, 04489/1 of blowing sand, taken just above the beach face at the same location as sample 04489/2 (Figure F3) is somewhat finer with d_{50} = 0.6mm and nothing finer than 0.25mm (2ϕ). This shows how strong wind selectively removes the finer sand particles from the beach.

During the 1989 investigation of the spoil dump, sand from the excavation for the new research station pumphouse was also examined (samples 30389/2, 3 and 4). This site is considered to be relatively undisturbed as far as recent human influence is concerned. Median sizes of 0.7 to 1mm were found with material up to 4mm present. However there was nothing finer than 0.25mm.

In summary, the natural beach sediments are medium to coarse sand which becomes finer towards the crest of the beach (Figure 50). The beach surface may at times be covered with a layer of finer sand deposited during low energy conditions. Coarser material, if present, tends to stay on the lower intertidal portion of the beach with distinct shingle swash deposits being formed for both the higher and lower high tides if such material is available. There is virtually no material finer than 0.2mm present within the beach material.

The shape of the beach profile is concave upwards with a slope of about 4^o near the reef flat increasing to 7^o to 8^o towards the berm crest. The profile of the sand spit shown on Figure 50 is somewhat flatter than these average conditions.

Observations on other cays in the Capricornia region and on Raine Island on the northern Great Barrier Reef confirm that these conditions are typical of beaches on sand cays on exposed reefs. However the original beach, which was partially moved to make the bund wall for the settling pond, may not have been a normal sand cay beach. Probings of that beach by research station staff in the past generally revealed 0.5 to 0.8m of sand underlain by large pieces of flat limestone rubble mixed with sand and further underlain by shingle. Consequently the original cay beach in the spoil dump area already had coral rubble in it and hence a deficiency of sand size material. On the other hand there is no evidence of silt or very fine sand, that is material finer than 0.125mm, being present in the pre spoil dump beach.

The source of the substantial quantity of rubble in the beach south of the helipad prior to the construction of the spoil dump has not yet been identified. There are several possibilities.

(i) It was placed there during the construction of the original boat harbour in 1966-1967. It is known that the helipad was constructed in 1968 on an area reclaimed using material obtained from this source.

(ii) It was moved there by wave action, particularly that generated by Cyclone David in January 1976. Prior to this event dredge spoil had been placed on the northwestern side of the island during maintenance dredging of the boat harbour in late 1972 following Cyclone Emily earlier that year. Most of this material had been removed from in front of the rock wall by October 1975 and virtually all of it was gone by December 1978. While it is clear that sand and shingle would have been moved by wave action from the northwestern side of the island to its southwestern side during this period, there is some doubt whether rubble would have been moved also.* This is particularly so since most of the material was moved to the southwestern sand spit before Cyclone David's cyclonic waves occurred.

(iii) It was placed there during the dredging of the harbour in 1980.

(iv) It is remnants of beach rock broken off the outcrops along the southern beach and transported westward by the larger southeasterly waves over a considerable period of time (see quote from Fosberg et al. 1961 in Flood 1974 where reference is made to large numbers of slabs of beach rock having been torn loose and strewn along the upper part of the beach on the south side of the island). Pieces of flat limestone rubble were visible on the upper beach behind the beach rock in July 1979 and this material appears to be similar to that described by research station staff as being found under the beach before the spoil dump was constructed.

4.4.3 Sediments on Spoil Dump Beach and its Vicinity.

Sediment on the spoil dump beach is derived from material within the spoil dump itself as there is little apparent evidence that sediments are being supplied to it either from adjoining beaches or the reef flat. Grain size distributions of sand size material obtained from holes A2 and C4 and typical of much of the spoil dump material, are shown in Figure F4 (samples 31389/1 and 03489/1. It is poorly sorted with a median size of 0.6 to 0.7mm. Particles up to 4mm are present while there is virtually nothing finer than 0.09mm apart from a few percent of silt.

Information about spoil dump beach sediments is not plentiful as attention during the field investigation was concentrated on the silt source, the spoil dump interior, and the assumed silt sink, the reef flat. A detailed beach profile approximately midway along the spoil dump beach was surveyed in May 1988 (Figure 50). Sediment samples were taken along the profile from the top of the spoil dump above the reach of the waves to the moat at the base of the beach.

The spoil dump beach profile in May 1988 was generally steeper than the pre-existing beach profile but does not have the sharp wave formed berm crest of the latter. This is a consequence of its artificial formation and maintenance. Small shingle berms are found just above the previous high tide levels on both the spoil dump beach and the natural beach.

Sediments on the spoil dump beach are not as well sorted as on the natural beach, particularly above high water mark where there is a wide range of particle sizes present (0.06 to >4mm) with 30 to 50% greater than 4mm (Figure F5, sample S1). Within the zone influenced by waves between the two shingle berms, sand is relatively well sorted with d_{50} of about 0.5mm (Figure F5, sample S3), virtually no material finer than 0.17mm and nothing coarser than 1mm. The sand coarsens further down the beach to a $d_{50} \approx 1.1$mm and there are increasing substantial amounts of shingle armouring the lower parts of the beach. Small amounts of very fine sand $d_{50} \approx 0.1$mm) are also present (sample S6) underneath the surface. There is negligible silt present on the active beach face or in the moat close to the beach (sample S7).

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* Dr Jell was present on the island during cyclone David and does not believe that rubble was moved on that occasion.

The effect of the dredging operation and the release of silt from the spoil dump can be seen in sediments on the reef flat in the vicinity of the spoil dump. Sediment samples were collected from the following areas in April and December 1989.

- beach and flat area between the boat harbour and the island along the line of the harbour leads;

- bottom of the boat harbour from the mooring basin to its entrance;

- reef flat along a line just south of the jetty and the southern row of concrete blocks for a distance of 100m seaward of jetty pile 8;

- moat and reef flat opposite the southern end of the spoil dump over a distance of 90m from the base of the beach;

- lower part of the western end of the beach rock;

- other locations within this general area.

In all cases some fine material is present. For example, in sample 04489/5 (Figure F6) from the boat harbour beach with d_{50} = 1.13mm, the main sand population has no material smaller than 0.5mm. This sediment is very similar to the coarser sediments found on the lower part of natural cay beaches, apart from a fine tail of material trapped within the voids of the sand matrix. Sample 06489/1A from the moat is similar, except that the main population is finer, d_{50} = 0.7mm, and there is a higher proportion (7%) of material finer than 0.063mm (4ϕ) present in this more sheltered environment. Again this indicates a natural beach or reef flat sediment which has been contaminated with silt.

Sediment collected from the flat behind the boat harbour (Figure F7, sample 04489/3A) is a more extreme example of silt-contaminated sediment. It is distinctly bimodal with silt (33%), sand (46%) and gravel (21%) present. Coarse beach sand with a modal size about 0.7mm is mixed with a poorly sorted silt fraction with a modal size of about 0.025mm. Interestingly sample 04489/6A from the bottom of the boat harbour, while showing a wide range of particle sizes is mainly sand (87%). This also is the case with sample 05489/7A (Figure F7) collected from the lower part of the western end of the beach rock opposite the research station. This sediment is bimodal with 0.7mm and 0.15mm sand populations present. The finer material is more plentiful and is assumed to have come from the spoil dump as material of this size was not found on the beach behind the beach rock.

In general, sediments collected in December 1989 from the reef flat near the southern end of the spoil dump are coarse sands with d_{50} = 0.6 to 0.7mm with a small amount of silt present, about 0.5% and not more than 1% (Samples P1 to P10). In the moat close to the spoil dump the sand may be coarser with d_{50} = 0.9 to 1.0mm and there is a small content of fine sand (Figure F8, sample P1). South of the jetty (samples Q1 to Q10) the sediments show a wide range of particle sizes with silt contents of 7 to 8% close to the beach and variable amounts between 0.5 and 4% further seaward. At least three sand populations can be identified. The dominant one is coarse sand, 0.6mm, but very fine sand, 0.1mm, and fine to medium sand, 0.3mm are also present. Sediments on the flat area landward of the boat harbour (samples R1 to R5) are similar, although locally there are zones with large amounts of silt and very fine sand, for example near the fuel post at the edge of the boat harbour (Figure F8, sample R5). In April 1989 some deposits of silt and fine sand up to 250mm thick were noted. They are generally cohesive and often grey in colour and smelly under the surface.

Within the boat harbour there is a wide range of sand and silt size material present. The amount of silt varies from one or two percent to over 20% (Samples 04489/6A, Ha1 to Ha7). Coarse, 0.6 to 0.7mm, medium, 0.3mm, and very fine 0.1mm, sand populations can be identified and there appears to be little logical pattern in their distribution except that sediments closer to the entrance are largely medium sand, are better sorted and have very little silt present (Figure F9).

In contrast to the above conditions, sand samples collected in July 1979 from the bottom of the boat harbour before its enlargement, when the ebb tide was flowing out to sea through the boat harbour because of breaks in the low rubble walls surrounding it, were much coarser (d_{50} >1.0mm) with virtually nothing finer than 0.3mm present. This material was sand from the reef flat or the island's beaches which had been transported into the boat harbour by the tidal currents. Finer materials may have been present in other areas of the boat harbour.

4.4.4 Silt in Spoil Dump, Plumes and Reef Flat Deposits

Silt deposits within the spoil dump are presumed to have been formed in the original settling pond into which the dredge pipe discharged. Analysis of several samples from the spoil dump gives very similar symmetrical grain size distributions (Figure F10). The range of particle sizes present extends from 0.0015 to 0.095mm (3.5 to 9.5ϕ) with a median size of the order of 0.01mm (6.75ϕ) (Samples 30389/1B, 30389/6B, 05489/2B and 05489/5A). Some silts are somewhat coarser with median sizes of 0.016 to 0.025mm (6 to 5ϕ) (Samples 05489/2A and 05489/6B from holes B0 and D1 respectively.

The grain size distribution of silt eroded from the spoil dump to form a silt plume is shown on Figure F11. Sample 30389/1B (Figure F10) represents silt from hole AH1 just behind the erosion scarp in the hardened silt south of the jetty. Sample 05489/4B is silt cementing the rubble in the scarp further along from the hardened silt deposit, while sample 05489/1A is from the silt plume being produced from that scarp on 5 April 1989. All are virtually identical with the other silt deposits in the spoil dump.

Silt deposited close to the spoil dump is coarser than that within the spoil dump or released in the silt plume. Sample 04489/8B is from a persistent silt deposit on the reef flat just south of the jetty near the base of the beach (see Figure F12). The size range is 0.004 to 0.5mm (8 to 1ϕ) with d_{50} = 0.034mm (4.75ϕ). 75% of this deposit is silt. Similar size material (Figure F7, sample 04489/3A) was found on the reef flat north of the jetty behind the boat harbour where 33% of the material was silt. In contrast, sample 06489/1AS represents the grain size distribution of the silt fraction from the moat sample 06489/1. The size range is 0.002 to 0.095mm (3.5 to 9ϕ) with d_{50} = 0.016mm (6ϕ). However only 6% of the total material in the moat sample is comprised of silt. 88% of it is coarse sand, 0.5 to 1mm.

The dispersal and deposition of silt particles suspended by waves eroding the spoil dump depends upon a number of factors. These include the height in the water column at which they were initially suspended by the breaking waves, the fall velocity of the particles in sea water of the prevailing temperature, the speed and direction of the resultant tidal and wind-induced currents on the reef flat, the scale and intensity of turbulence within the currents as well as that induced by wave action, electrochemical or other processes causing particles to clump together, etc.. The whole process can be quite complex and, in the absence of suitable models to predict current velocities and flow patterns on the reef, no definite predictions can be attempted. However, some indications of depositional behaviour can be deduced from a knowledge of fall velocities for silt particles and the known grain size distributions for material forming silt plumes.

Fall (settling) velocities of bioclastic sand and shingle particles are known to be very significantly affected by the shape and bulk density of individual particles. Measured values of fall velocity may be much less than those calculated from relationships based upon an equivalent spherical particle of density equal to that of calcium carbonate (Maiklem 1968, Braithwaite 1973). However for silt particles, variations in both shape and density are not likely to be as significant as for larger particles. Hence it has been assumed that the silt particles are spheres of specific gravity 2.8, settling in accordance with Stokes Law through water of 25^{o}C temperature. Provided that there is no significant clumping or flocculation of particles, the values so calculated are likely to overestimate the rate of settling of particles in the silt plumes at Heron Island.

Stokes Law assumes that viscous drag on the surface of the particle dominates in determining the fluid resistance to the free fall of the particle under the influence of gravity. Under these conditions the fall velocity of a spherical particle of uniform density is given by the following relationship

$$w = \frac{gd^2 (s-1)}{18v}$$

where	w	is	fall velocity of particle
	d	is	particle diameter
	s	is	specific gravity of particle
	v	is	kinematic viscosity of water
	g	is	gravitational acceleration

Table 6 gives values of w for silt size particles at increments of one ϕ particle size, together with the time it would take them to settle through a water column 2m high. For comparison with these values, the maximum rate of rise of the tide can be obtained from the following relationship

$$\frac{dy}{dt} = \frac{\pi A}{T}$$

where $y = \frac{A}{2} \sin \frac{2\pi t}{T}$ is the tidal water surface elevation

t	is	time
A	is	the tidal range
T	is	the tidal period

Table 6. Fall Velocities of Spherical Silt Particles specific gravity = 2.8; water temperature 25°C.

Particle φ	Size mm	Fall Velocity mm/s	Time to fall 2m
4	0.063	4.29	8 min
5	0.031	1.05	25 min
6	0.016	0.29	2 h
7	0.008	0.07	8 h
8	0.004	0.017	32 h
9	0.002	0.004	130 h

For a semidiurnal tide, T = 12.42h and, for tidal ranges between 2 and 3m, the maximum rate of rise of the tide at mean tide level will be 0.51 to 0.76 m/h or 0.14 to 0.21 mm/s. These values are comparable with the fall velocities for particles of 0.011 to 0.014mm size. Such particles take 4 to 2.5h to settle through a depth of 2m.

Consideration of grain size distributions for sediments from specific locations leads to the following deductions.

(i) Material coarser than silt (0.063mm) is unlikely to be moved far from the spoil dump under normal conditions since it settles quite rapidly, i.e. in 8 minutes or less;

(ii) material of the order of 0.031mm size is likely to be found fairly close to the spoil dump since it only takes 25 minutes to settle through 2m water depth. Hence, if suspended by waves at high tide when tidal currents are negligible, it may only move a short distance offshore. The deposit on the reef flat south of the jetty opposite piles 7 and 8 would be consistent with these figures. Its location is probably the result of low bottom current velocities caused by the blocking effect of the concrete block wall on currents.

(iii) Silt found on the reef flat or in the boat harbour has negligible amounts of material finer than 0.008mm. Clearly as particles smaller than this size take more than 8h to reach the bottom from a 2m height, they should be generally removed by the ebb tide following the high tide during which they were suspended.

(iv) Insignificant quantities of particles finer than 0.004 are found in the spoil dump sediments. This could mean either that the settling pond was not effective in retaining such small particles or that such particles were not present in the dredged material. Both may be true. Certainly the settling pond was not very effective in its operation and is unlikely to have had a retention time of 32 hours required to deposit 0.004mm size particles. On the other hand, no water samples collected from plumes generated during the dredging operation or from the settling pond during its operation are available to determine the nature of the material actually dredged.

(v) The exposed surface of the reef flat should be generally clear of particles smaller than 0.01mm, since wave action will stir up and suspend all sediments smaller than 0.15mm. Many such particles will be removed from the reef flat by ebb tide currents. As particles 0.01mm or smaller take 4 hours or more to settle through 2m depth, there is a high probability than most of them will be removed during the following ebb tide.

4.5 Silt Plumes

4.5.1 Plumes Generated during Boat Harbour Enlargement Works

Study of photographs (QNPWS and HIRS) indicated that, during construction, silt plumes were generated, not only from the settling pond, but also from the immediate area of operation of the excavator and the dredge (Photos 12 and 13).

Study of wind observations and discussion with observers on the island lead to the conclusion that, not only the tidal flow, but also the wind direction was very important in determining the direction of the plume. During the first two weeks of the construction period, winds were generally SSE to ESE, changing to generally NW to NE during most of October and becoming generally ENE to ESE during early November. Occasional anomalies with moderate to strong wind from a different direction occurred during these periods.

The effluent plume from the settling pond ran back into the harbour. At low tide the plume discharged from the harbour entrance and under the influence of the persistent northerly winds flowed along the edge of the reef in a southeasterly direction. On the one occasion, 18 October 1987, when the silt plume from the harbour was photographed moving in a northwesterly direction along the reef edge, the winds were blowing from the south. On a rising tide under northerly conditions, the silt plume travelled over the reef flat along the southern side of the island. The plume from the settling pond tended to travel close inshore along the moat at the edge of the beachrock towards the lagoon (Photo 2). Photographs show a second independent plume further out from the shore, originating from the dredge and excavator working in the boat channel. At high tide and early ebb, these plumes would spread out over the southern reef flat (Photo 14).

With southeasterly winds on a rising tide, the silt plume from the settling pond would travel around the western end of the island, part of it moving across the northern reef flat to the reef edge, while the other part moved close inshore eastwards along the northern beach to the eastern end of the island. On high tide and early ebb and southeasterly conditions, the plume would spread and dilute over the northern reef flat.

A more detailed description of the behaviour of the plumes based on observations by Heron Island Research station personnel is given below.

"At low tides, (outgoing) plumes originating from the tailings dam and harbour operations flowed out of the harbour and along the upper reef slope/crest area to the south-east. As the tide turned, this plume (which extended over two kilometres to the south-east at times) slowly arched away from the crest and spread into the middle of the Heron-Wistari Channel. Areas adjacent to the harbour entrance were engulfed in this plume for approximately six hours over each low-tide period. Areas further to the south-east experienced progressively less time in the plume. Areas north-west of the harbour entrance were also affected during the early periods of the incoming tide. The incoming tide picked up the fine material from the dredging operation and the tailings dam and carried it around both sides of the cay where both plumes joined together and continued up into the lagoon to the east of Shark Bay. Occasionally, a plume also extended around the northern reef slope edge beyond the popular 'Blue Pools' diving location. The northern reef flat seemed to be less affected by the sediment plumes, though a fine layer on everything was evident. The plume extending up the inner, southern gutter on the incoming tide slowly changed course as the tide turned and gradually moved around to the south and then northward and westward, perpendicular to the beach, resulting in the whole southern reef flat being inundated. It was estimated that the inner gutter area on the southern flat adjacent to the cay (as well as that distance again eastwards towards the lagoon) experienced high sedimentation of very fine material for at least 12 hours of a 24 hour cycle. The sea-water intake for the Research station's aquaria sucked in these sediments and for several weeks the aquarium water supply contained these sediments in suspension. As a result of this, the majority of the organisms contained in the aquarium tanks died. The mid and outer reef flat experienced less time in the plume, a period of approximately 4-6 hours per tidal cycle (24 hours). The lower half of the beach rock on the southern side of the island was covered with several centimetres of fine silt which has persisted for six months to date in this area" (HIRS-RRIS 1988).

4.5.2 Plumes Originating from Spoil Dump

The daily visual observations of conditions affecting the spoil dump included a sketch of the extent of the silt plume, if one was observed. These observations are affected by the ambient light and weather conditions at the time of observation and the sketches are not accurately drawn when compared with the observed silt plume widths at stations 1 and 2. In many cases the estimation of the plume width itself is uncertain as the turbid zone is not always well defined or there may be zones of distinctly different turbidities present. Nevertheless some general characteristics of the plumes generated from the spoil dump can be discerned.

Firstly, the silt plumes commonly extend further seaward than the breaker zone of the waves causing them. Indeed plume widths are generally several times greater than the surf zone width. Secondly, silt plumes generally increase in extent as the breaker height increases. Thirdly, since the observations were made within an hour or so before high tide, the recorded plumes show negligible influence of tidal currents but indicate the effects of wind-induced and wave-generated currents upon plume movement. Some of the characteristics of the spoil dump plumes are shown with the selected cases given in Figures 52 to 54.

The effect of wind direction is given on Figure 52. In the first case, small waves (H_b = 0.2m) generated by 15kn southeasterly winds broke on the eastern end of the spoil dump with negligible wave action near the jetty. A narrow plume was generated which moved downwind, separating from the beach and passing under the jetty before dispersing in the boat harbour. In the second case, 25 to 30kn southerly to southsouthwesterly winds generated 0.4m waves which created a narrow plume originating near station 2 and extending in a narrow band northwards along the shoreline. A similar condition is shown in the third case, the difference being that the 15kn northnorthwesterly winds moved the plume in an easterly direction. Onshore winds will generally confine the silt plume close to the shore, whereas offshore (easterly) winds will disperse it seawards (Figure 52d).

The second group of silt plumes (Figure 53) shows the general development of silt plumes with increasing wave height and tide level. Wind directions were easterly to southsoutheasterly. The extent of the plume clearly increases with wave height from a very localised turbid zone as on 29 July 1989 (event E2) to an expansive zone which extends to the reef rim as on 19-20 August 1989 (event E3). Distinct zones have been recorded with medium sized wave heights with an inner very milky zone close to the spoil dump and an outer more diffuse zone on the reef flat. The cause of these zones of different turbidity is not easily defined. In some cases rainfall may wash silt from the surface of the spoil dump into the sea. In other cases the waves are clearly large enough to stir up sediments from the reef flat so that the observed silt plume is formed of silt originating from both the spoil dump and the reef flat.

The effect of rain in contributing to the silt plumes is shown in the third group of plumes (Figure 54). These were observed during event E8 when east to eastsoutheasterly winds generated medium sized waves (0.3m) at higher high tides
(_ 3.0m). Quite small amounts of rain (_ 5mm) resulted in distinctively streaked plumes, the direction and location of which fluctuated with the wind direction. Similar types of plumes were observed on at least three other days during the three months preceding event E8. Rainfalls were not very large but wind speeds were generally greater than 20kn. The distinctive streaked plumes generally associated with rainfall probably result from either localised runoff from exposed silt deposits or groundwater outflow from silt-rich zones during the lower tide levels preceding the observation at high tide.

Rain by itself does not necessarily produce silt plumes. During 2 to 3 April and 16 to 19 April 1990, heavy rain was recorded (totals of about 200 and 300mm respectively). Tides were low (< 2.0m) and waves were negligible. No plumes were observed. Apparently, all loose silt had been removed by preceding events. Alternatively, visibility was so bad that plumes could not be seen.

Finally, it should be noted that human activity will contribute to the occurrence of silt plumes. This has already been noted with respect to beach reshaping during event E1 in late May 1989. Another such situation occurs when vessels use the spoil dump beach for berthing purposes. On 15 November 1989 when the tide was high (3.0m) but waves negligible (0.1m), a barge landing near station 1 created a 2m wide silt plume at the eastern end of the spoil dump. Boats, particularly the larger ones, also stir up fine sediment on the bottom of the boat harbour and produce local silt plumes. This effect is most pronounced at low tide when the boat harbour is isolated from the reef flat and it is probable that most of the material settles back into the boat harbour before the tide has risen high enough for the plume to be carried onto the reef flat.

4.5.3 Plumes around Island

It was intended to use a Partech 700 BRP suspended solids monitor to map the extent of the silt plume about the island and across the reef flat. During normal weather conditions the silt plumes were narrow and close to the island as shown in figures 52a, b and 53 e, f, with readings up to 50 ppm near the spoil dump, falling away to 3 ppm near the edge of the plume, and 0 to 3 ppm over the rest of the reef flat. Only when the winds reached 20kn and the wave height and tide levels were high enough were extensive plumes generated. In these conditions it is dangerous to have observers take the instrument out in small boats. However, a series of readings was taken on 13 December 1989 when the wind was 20 to 25kn gusting to 38kn from the southeast. The readings were taken just before high tide and on the early ebb (about 1.5 to 2h after high) tide and showed that the plume moved around the western end of the island and out to the north (Figure 55). The most dense parts (up to 80 ppm) were in the lee of the island on the inner reef flat adjacent to the resort (Figure 55). Analyses of water samples taken during this survey, showed that the suspended solids over most of the reef flat varied from 0.0007 to 0.011 g/l with one sample from the most dense part of approximately 50 ppm giving 0.169 g/l.

4.6 Monitoring of Reef Flat Sediments

4.6.1 Sediment Distribution before September 1987

Prior to September 1987, sedimentological studies of reef flat sediments of Heron Reef had been undertaken by Maxwell, Day and Fleming (1961), Maxwell, Jell and McKellar (1963, 1964), Flood and Jell (1977), and Jell and Flood (1977). Jell also has data collected during student field classes at Heron Island for the period 1980-1987. However, the results of these studies do not lend themselves to precise comparison with those of the studies since 1987. Maxwell *et al.* collected samples in open cups; Flood, Jell and the students used plastic bags scooping sediment into the bags, bringing the bags to the surface, allowing the fines to settle, then decanting off excess water; both methods may not have retained as much of the silt and clay fractions as the method using screw topped jars. Also the students' data can only be used for the broadest of comparisons, as the sieving was hand shaken for various periods of time. In the earlier studies, slightly different granulometric parameters were calculated; those used in the present study are those used by Flood and Jell (1977).

Sediment is distributed by wave action (breaking and oscillatory), and tidal and wind generated currents across the reef top. In general the sediments are distributed in a concentric-horizontal gradation across the reef top. The general trend is from very coarse sand and gravel around the outer reef rim and outer reef flat to very fine sand and silt at the reef centre corresponding to the lagoon. This pattern is interrupted at the western end of Heron Reef by Heron Island and the runoff through the boat harbour and channel. In the latter area, the water flow through the harbour channel is considerable and the fine sand is soon winnowed out. The outer coarse material grades into an area of medium sand covering the remainder of the reef flat around the island. With the continued run off through the harbour and a general westward transport of material from the lagoon during periods of strong southeasterly weather, fine sediments ($d_{50} <$ 0.50mm; 1ϕ) from the lagoon intertongue with the medium sands of the reef flat. The width and depth of the penetration of the fine material have varied considerably over the period 1980-1987, especially after cyclonic periods.

The distribution pattern for the graphic standard deviation shows that the sorting in the area adjacent to the island is controlled by the runoff through the harbour on the ebb tide. Bands of well sorted sediments occur on the outer reef flat on both sides of the island directed towards the harbour paralleling the maximum ebb tide runoff.

The composition of the sediments consists of detritus from five organic groups in decreasing order of significance: coralline algae, corals, *Halimeda*, molluscs, and foraminiferans. The distribution of these components is detailed in Jell and Flood (1977).

Jell and Flood (1977, fig. 19) compared the median size and sorting coefficient patterns from their study of August 1975 with Maxwell *et al.* (1961). When Maxwell *et al.* sampled the area, a small gap had been blasted in the reef rim adjacent to the wreck and there was some runoff through this gap at low tide.. Between 1961 and 1977, the harbour was initially dredged in late 1966 - early 1967, increasing water flow and lowering of the level of water over the reef flat adjacent to the harbour. The harbour and channel continually filled in and had to be redredged several times (Section 2.1). These changes altered the water flow considerably resulting in changes to the hydraulic regime in the area, and consequently the sediment distribution.

Flood and Jell (1977, fig. 3) plotted their data for August 1975 using the graphic mean size and graphic standard deviation coefficients for mean grain size and sorting, respectively. They also showed the change in distribution pattern after cyclone David in 1976. The data from the students' mapping suggests that the pattern during the early 1980's shows a trend back to the precyclone pattern. Thus for this study, the distribution pattern of August 1975 is used as a guide for the pre-1987 pattern (Figure 56B). The students' data for 1980-1987 would suggest that the August 1975 pattern was similar to the 1985-1987 patterns.

In general, very coarse to coarse sand and gravel ($d_{50} > 1$ mm; 0ϕ) dominates on the reef rim and this zone is broader on the northern rim and about the harbour where it extends from the reef edge to the beach.

4.6.2 Sediment Distribution after September 1987

The graphic mean size and graphic standard deviation for all samples were plotted and contoured for each survey. The plots of the graphic mean size for December 1987, 1988, and 1989 are the most instructive (Figure 57) The graphic standard deviation plots do not show any major trends (Figure 58). To ascertain the significance of the silt fraction in any change in mean size distribution, the silt size content (as a percentage of total sediment) was plotted (Figure 59). Although generally less than 2 percent, the changes parallel the changes in mean size.

Compared with the 1975 distribution pattern, the post 1987 patterns show a broadening of the zones of very coarse sand and rubble of the outer reef flat and reef rim, especially on the western tip of the reef. From the crude data of the students' surveys in the 1980's this change appears to have been gradual and not related to the dredging in 1987. The distribution about the eastern end of the Island is very similar to that prior to the dredging, especially allowing for the variation that occurs after long spells of southeasterly weather.

The major changes in the sediment size distribution occurred adjacent to the harbour and across the northern reef flat, immediately north of the western tip of the island. An area of fine sediment ($d_{50} < 0.50$ mm, 1ϕ) developed across the reef flat south of the spoil dump, adjacent to the harbour and extending eastwards for up to 250 m. In 1987, another patch of very fine sediment occurred close to the reef rim southeast of the wreck. In the area north of and adjacent to the harbour and extending as a tongue northwards across the reef flat the sediment became finer. These are areas where the sediment derived from the spoil dump would be deposited. On the ebb tide, transport of eroded material would be southwestwards with the material being deposited across the reef flat. On the top of the flood tide and especially during southeasterly weather, transport is around the western end of the island and northwards across the reef flat.

Comparison of the 1987 and 1988 surveys, shows that these areas of finer sediments rapidly returned to the pre-1987 pattern. However, in 1989, there was a patch of finer material immediately south of the spoil dump, but it is considerably smaller than that in 1987. Histograms for 1987, 1988 and 1989 samples from the outer reef flat southeast of the wreck, inner reef flat off the spoil dump, and inner reef flat 300 m north of the western tip of the island, show that decrease in graphic mean size appears to be due to the loss of material finer than 0.25 mm ($2\ \phi$), i.e. fine sand and smaller (Figure 60). This is the size range of material that is taken into suspension under normal weather conditions (see section 4.4.4).

The plots of graphic standard deviation for 1975, 1987 and 1989 show little change, except for an area of very poor sorting southeast of the wreck on the outer reef flat in the area of fine sediment immediately after the dredging in 1987 (Figure 58A).

Unfortunately data on the silt and clay content (< 0.062 mm, 4ϕ) of the sediments prior to September 1987 is not available. Plots of the silt content for 1987, 1988, 1989 surveys show concentration of more than 10% in some sediments in the area of *Pocillopora* and branching

Acropora east of Shark Bay (See Figure 4 for location). In December 1987, a band of sediment with more than 1% silt stretched along the inner reef flat on the northern side of the Island to the northeastern end of the island (Figure 59A). In 1988, this band had broadened further and extended around the western end to the harbour (Figure 59B). In 1989, it broadened further, especially on the reef flat north of the sand spit on the northeastern end of the island (Figure 59C).

In 1987, the other occurrence of sediment with over 10% silt was on the outer reef flat immediately southeast of the harbour entrance where samples had up to 40% silt. This area was surrounded by a narrow zone of 1 to 2% silt. In the remainder of the area about the harbour and the spoil dump, silt content was less than 1% (Figure 59A). In 1988, the area of distribution of sediment with more than 1% silt increased southeast of the harbour extending from the spoil dump to the reef rim but the silt content never exceeded 2%. Northwest of the harbour there was also a large area of 1 to 2% silt (Figure 59B). In December 1989, a similar distribution existed but with a small patch of 2.0 to 2.5% silt off the western end of the island (Figure 59C).

4.6.3 Synthesis of Sediment Distribution Patterns on the Reef Flat.

Effluent from the dredging operations and erosion of the spoil dump while dredging operations were under way, contributed large quantities of mainly fine sediment probably less than 0.50 mm (1ϕ) to the surrounding area. The coarser fractions of this material would have been deposited in the area south of the spoil dump and to the north of the western tip of the island. This would account for the initial increased amounts of the finer material in these areas.

Observations by the HIRS staff report the deposition of large quantities of fine sediment along the outer reef flat, reef rim and reef slope southeast of the wreck during the dredging in September 1987. This would account for the high silt content in this area in the December 1987 survey.

It appears that the dredged material had little effect on the overall sediment distribution on the southern reef flat east of the Research station and on the northern reef flat east of the resort. Some of the fine silt size material may have settled in the area of *Pocillopora* and branching *Acropora* east of Shark Bay as the silt plumes were seen to extend to that area. However, this is the area that also receives considerable fine material from the lagoon in strong southeasterly weather and the amounts from either source cannot be determined.

Following the initial distribution of dredged material, the sediment distribution pattern began to be modified by the normal transport agents of waves and tidal currents. Apart from the normal supply of fine material from the lagoon, there was a source southeast of the wreck that in high energy conditions could be taken into suspension and redistributed on the reef flat or transported off the reef. There was also the material being eroded from the spoil dump under the conditions outlined in section 4.2. In the two years of the monitoring, the fine material, particularly the silt (< 0.062 mm, 4ϕ), has been redistributed and much of it removed from the reef. The distribution pattern is essentially returning to what it was prior to the dredging. It will be modified somewhat in the area of the harbour because of the continued supply from the spoil dump and because the currents on the last of the ebb tide have been modified by the rubble walls and blocks about the harbour.

4.7 Monitoring of Sediment-affected Beach Rock

Examination of the beach rock affected by the sediment was carried out each time Dr Jell visited Heron Island (Section 3.2). No quantitative data was taken since the amount of sediment and the effect on the biota were being monitored by HIRS (see Chapter 1).

In December 1987, the western end of the beach rock was covered in fine sediment which seemed to be mainly silt with some fine sand. At the base of the beach rock it was 50 mm thick and in places up to 100 mm. Beneath the top 10 mm it was dark grey and probably anaerobic. On the upper parts of the beach rock it was of the order of 2 to 10 mm thick but up to 30 mm thick in small hollows. The whole of the western third of the beach rock was covered to this extent (Photo 15). Further to the east the amount of fine sediment decreased but it could still be seen on the eastern end, especially in hollows in the beach rock. Where it was less than 5 mm thick, it appeared to be trapped by filamentous algae and in places coated by algae.

On subsequent visits the amount of sediment on the beach rock gradually decreased so that in December 1990 most of the upper part of the beach rock was clean of fine sediment except for a few deep hollows. There was still a layer, up to 10 mm thick on the lowest parts on the western end, just in front of the Research station (Photo 16).

Most was washed away by normal wave and tidal action. However, in the upper parts where the mud was encrusted by algae, it would dry out during low tide and crack with the edges turning up (Photo 17). Often these algal mud flakes would detach themselves from the rock. On the incoming tide these may be washed away removing a considerable amount of silt at one time.

4.8 Lithification and Vegetation of Spoil Dump Material

The surface of the spoil dump, especially that part where the vehicles are continually crossing it, has become very compacted. Samples were taken and then sectioned but no sign of a calcareous cement was detected. Similarly, an area by the boat harbour where the tractors continually drive over it appears consolidated. The loose sediment has been washed away from it and it stands with a relief of up to 20 mm in part, consisting of coarse rubble in a fine sand and silt matrix. Samples taken show no signs of permanent cementation. It appears that it is consolidated mainly by compaction. Areas where rain water lies for some time after rain were also examined but no sign of cementation was recognized.

The first vegetation on the spoil dump was noted in December 1989 when at least 10 specimens of *Sisymbrium orientale* appeared on the outer edge of the spoil dump south of the jetty (Figure 7). Its extent and diversity subsequently expanded considerably. Dr R. Rogers of the Department of Botany, The University of Queensland noted 44 plants of 8 species in June 1990 and 299 plants of 14 species in November 1990 (Table 7). The vegetation is confined to the area not crossed by vehicles (Photo 18). It is stabilizing and trapping the fine sediment and with time should accumulate a quantity of fine wind blown sediment. The extent of the area covered by vegetation in June 1991 is shown on Figure 8.

Table 7. Species and number of individuals of plants recognized on the spoil dump at Heron Island.

Species	December 1989	June 1990	Nov. 1990
**Amaranthus viridis*	-	-	1
Argusia argentea	-	-	8
Boerhavia tetrandra	-	2	5
Cakile edentula	-	10	37
**Calyptocarpus vialis*	-	3	-
**Capsella barsa-pastoralis*	-	5	1
**Eleusine indica*	-	5	12
Gnaphalium lutea-album	-	-	2
**Lepidium virginicum*	-	-	200
Lepturus repens	-	1	3
**Poa annua*	-	-	3
**Portulaca oleracea*	-	-	14
Sesarium portulacastrum	-	-	2
**Sisymbrium orientale*	10	18	8
Tribulus cistoides	-	1	3
Total Species	1	8	14
Native Species	-	4	7
Total Individuals	10	45	299

Identifications by Dr R. Rodgers, Department of Botany, The University of Queensland.

* Introduced weed species.

5. ASSESSMENT OF OVERALL SITUATION

(i) The quantity of fine sediment released during the dredging operation and from erosion of the spoil dump in the period immediately afterwards, was substantial and significantly altered the sediment distribution pattern on the reef flat. With time, this fine material has been winnowed out and the distribution pattern is now returning to that expected under natural conditions.

(ii) Initially, it was reported that the fine material formed a thin layer on the reef flat but was soon taken into suspension and mixed with the coarser material normally present on the reef flat or removed from the reef top altogether. By the time of the first sampling in December 1987, there was no evidence of such a layer nor of anoxic conditions within fine material on the reef flat.

(iii) The beach rock, especially that on the southern side of the island, was covered initially by considerable amounts of silt and fine sand. Except for the lower seaward region of the western end of the beach rock immediately east of the spoil dump, the beach rock is now (Dec. 1991) almost completely clear of significant accumulations of fine sediment.

(iv) Areas of the surface of the spoil dump are relatively consolidated due mainly to compaction by the continuous traffic of heavy machinery over these areas, rather than by natural cementation. The areas not subjected to such traffic, especially the seaward margin of the dump, are being colonised by vegetation.

(v) The initial volume of the spoil dump in December 1987 has been estimated as 14860m^3 relative to August 1984 beach contours. This volume has been reduced by 1780m^3 (12%) during the three and a half year period to June 1991. It is estimated that about 10% of the material in the spoil dump is silt.

(vi) Silt is very unevenly distributed within the spoil dump, often being concentrated in lenses, and generally it is more prevalent in the northern part of the spoil dump near the jetty. This is also the region of strongest wave attack. The silt in the highly concentrated zones develops cohesion on drying. When exposed, this cohesion is sufficient to maintain a vertical erosion scarp up to 0.5m high. Erosion resisting deposits also exist on the reef flat between the boat harbour and the beach.

(vii) Silty material is being released into the reef-top waters when waves erode the seaward face of the spoil dump. As the size of the waves increases with both wind speed and tide level, silt plumes are more likely to occur when winds are strong and tides are high. They do not occur on most occasions when wind speeds are less than 15kn, average breaking wave heights less than 0.2 to 0.3m and high tide levels less than 2.5m. Prior to January 1991, the incidence of silt plumes was decreasing. However, there was a substantial increase in the number of plumes during that month following the renewed exposure of silt. Nevertheless in April 1991 the silt plumes were less extensive than they were two years earlier. The influence of rainfall upon the occurrence of silt plumes is not simple nor as significant as winds, waves and tide level.

(viii) Erosion of the northern end of the spoil dump near the jetty is primarily caused by waves coming from the northern side of the reef, whereas erosion of the southern end of the spoil dump is caused by waves coming from the southern side of the reef. More silt plumes are generated at station 2 near the jetty than at station 1 at the southern end of the spoil dump. This is because breaking waves during the period of observation were generally larger at station 2 than station 1 and there is more silt in the vicinity of the jetty than further south.

(ix) The two occasions when significant erosion of the spoil dump occurred, exposing silt deposits and causing increased silt plume occurrences, were both associated with swell, originating from distant cyclones (Aivu in April 1989 and Joy in January 1991) and coming over the northern reef edge on very high tides.

(x) During the process of erosion and reshaping of the seaward face of the spoil dump, the silt is carried away by currents and either deposited on the reef flat or removed from the reef platform. Sand and shingle are redistributed to form the new beach profile and new beach alignment. Rubble generally remains on the beach at the base of the erosion scarp until removed by human action, generally to protect the jetty or the helipad or to provide easy access to boats anchored on the reef flat.

(xi) The shoreline of the spoil dump is being realigned by the present dominant waves into a new "stable" equilibrium form. Waves from the north breaking at an angle to the shoreline are attempting to form a crenulate bay shape south from the southern end of the timber wall protecting the helipad. This process is causing considerable erosion in the vicinity of the jetty and is being modified by human activity involving the placement of rubble to reduce erosion. The southern portion of the spoil dump and its adjoining beach have been realigned to be parallel to the crests of waves coming over the reef edge to the south of the boat harbour. In both cases the realignments appear to be a response to negligible net alongshore sediment transport towards the spoil dump.

(xii) The initial direction of movement of the silt plume when erosion occurs at high tide is normally dependent upon the wind direction. As the tide commences to fall, the plume will move with the ebb tide along the moat towards the boat harbour and then seawards along the southern side of the southern harbour bund wall. Outflow into the ocean occurs either over the reef rim immediately south of the wreck or through a low point in the bund wall at the landward end of the wreck, and then out through the boat channel.

(xiii) Material in the silt plume is predominantly silt and has essentially the same size distribution as the silt found in the spoil dump. The extreme size range is 0.0015 to 0.095mm but most of the material (>90%) lies between 0.004 and 0.06mm with the median size being about 0.01mm. Silt deposited on the reef flat closer to the spoil dump is somewhat coarser (d_{50} _ 0.03mm) than that released in the plume. Negligible amounts of material finer than 0.008mm were found on the reef flat and this is consistent with the very long settling time for such particles which is of the order of 8h to fall through a depth of 2m. Such particles will be removed from the reef flat by tidal currents after being stirred up by wave action.

(xiv) The conditions under which fine material is released from the spoil dump by natural causes are different from those which created the extensive plumes and deposits during construction of the boat harbour. During that period, excavation, dredging and overflow of the settling pond would have occurred at various states of the tide including the flood tide. Moreover silt plumes were generated from various locations along the boat channel. Northerly winds dominated on most occasions and these would have assisted the flood tides to move silt plumes eastward across the reef flat and along the moat. Now, erosion of the spoil dump is mostly only possible under conditions when the plume moves seaward fairly soon after its generation.

(xv) The meteorological events which generate the waves which are eroding the spoil dump may extend over several days or more but the actual release of sediment onto the reef flat is in a series of separate pulses defined by the tidal rise and fall associated with each high tide. Erosion will occur and a silt plume develop as the tide rises above a level of the order of 2.5m. With the dominant eastsoutheasterly to southeasterly winds the plume should be confined to the region near the spoil dump before the ebb tide moves it offshore, either through the boat harbour or across the reef flat just south of the harbour. Only on occasions of strong northerly winds and very high tides, are significant eastward movement of sediments and their depositon on the beach rock or reef flat further east likely to occur before the ebb tide begins to control the movement of the silt plume.

(xvi) Under natural conditions, the larger waves crossing the reef-flat will stir up existing sediments, putting them into suspension, and creating turbidity. Some of these naturally suspended sediments will be caught in reef-top sediment traps, even though no net accumulation of sediment is occurring on the reef flat. Hence, sediment traps may overestimate average accumulation rates. Furthermore, when the waves subside, the coarser suspended sediments will be deposited relatively rapidly during a comparatively short period. Consequently the actual rate of deposition during this period may be much greater than the average rate determined over a week or month or whatever the period between emptying the trap may be. Hence significant deposition may occur on the reef flat under natural conditions with no additional sediment being supplied to it. Moreover actual deposition rates during short periods of time may be much greater than average rates over longer periods. The ecological impact of this deposition could depend upon the amount of sediment suspended, the rate at which it settles and its timing relative to the life cycles of marine organisms.

(xvii) During the period of monitoring, recorded wind velocities did not exceed 35 kn and the highest predicted tide level was 3.25m. Stronger winds are known to have occurred in November 1988. The anemometer did not function properly then but 40kn winds are believed to have occurred. Earlier, cyclonic winds of 70 to 80 kn were recorded at Heron Island during cyclone "Simon" in February 1980. If this situation reoccurs, coinciding with a very high tide, waves of the order of 1.5m maximum height could reach the spoil dump and cause substantial erosion, involving reshaping of the beach and realignment of the shoreline. These changes could be accompanied by the release of substantial quantities of silt. However once released in this way, much of the silt is also likely to be removed from the reef platform by tidal and other currents, either during the cyclone or other occasions when waves stir up sediments on the reef flat.

6. CONCLUSIONS

6.1 Specific Conclusions relating to Heron Island Spoil Dump

Overall in the 42 months following the enlargement of the boat harbour the frequency and extent of silt plumes has reduced significantly, although recently there has been an increase in plume frequency following an erosion event exposing a fresh silt scarp in early January 1991. Silt plumes are unlikely to occur unless the wind speed exceeds 15kn and the tide level exceeds 2.5m. During this period much of the fine material released has been transported off the reef top.

Approximately 10% of the material in the spoil dump is silt and by June 1991 about 12% of the total volume of material has been removed from the spoil dump. The seaward face of the spoil dump has been reshaped and realigned with the "normal" wave action from both the northern and southern sides of the reef. Erosion at the jetty is being resisted by rubble which has been transferred by mechanical means from the beach face on other parts of the spoil dump.

The large amount of coarse material present in the spoil dump makes its beach unpleasant to walk on, not visually attractive and obstructs turtle nesting. The advantages are that the shoreline is likely to remain fairly stable except during extreme events, e.g., cyclones. The spoil dump is thus effectively a reclamation which increases the area of the island and gives space for storage of construction materials, boats, etc., without requiring destruction of vegetation and bird nesting habitats elsewhere on the island. However, this use compounds the visual unattractiveness of the area. It will remain unattractive unless such activities are restricted so that vegetation can develop and be maintained.

Significant erosion and change of the spoil dump shoreline in the short term are only likely with large waves at higher high tides. Such conditions are most likely to occur during cyclones or strong sustained southeasterly winds or heavy swells. While increased amounts of silt will be released from the spoil dump under such conditions, they are also expected to create conditions favourable for the removal of fine sediments from the reef flat.

Continued routine monitoring is required so that conditions causing change are recorded, the effectiveness of management actions can be assessed, and baseline observations are available for future maintenance dredging or new capital works associated with the boat harbour or other facilities in its vicinity.

6.2 Some General Observations concerning Environmental Monitoring

During the period of observation conditions were mainly relatively calm. Hence environmental managers and others can be lulled into a false sense of security. Climatic variations from year to year mean that few years (periods) are "average" or "typical" ones. Erroneous conclusions with regard to environmental conditions thus can be made easily since most periods of observation are too short. This applies to both preproject baseline studies and postproject monitoring programmes.

Environmental impact assessments are of limited use unless the public authorities responsible for protecting the general public interest ensure that the project has been constructed in accordance with the approved plans and that its environmental performance, as well as other aspects of public concern, e.g. safety, meet the specified standards appropriate for that project. In this case the postproject implementation of the monitoring programme was inhibited by the absence of any survey of the spoil dump and adjoining shoreline immediately following project completion. The only work-as-executed plan available was a postdredging survey of the boat harbour showing the jetty but not the spoil dump. Furthermore, in this case, much valuable information was not obtained because the monitoring programme was not commenced until more than twelve months after the completion of the project.

Individual perceptions of events vary greatly. Emotive reporting of an event without an adequate sense of its scale within the overall system or an understanding of the processes involved may be misleading. For example, reported "severe" erosion at the jetty might actually be relatively small in comparison with the whole spoil dump; observed "massive" resurfacing of the spoil dump by earthmoving machinery might result only in a small change in surface levels even though it appears to the observer that a considerable amount of rubble has been redistributed; "vast" silt plumes actually might be only quite localised with respect to the whole reef and may dissipate quite quickly without significant adverse effects. Nevertheless such reports may also highlight significant factors overlooked by project planners and environmental managers. This may be so, particularly when decision makers are located away from the site, do not have reliable on site knowledge, or lack a sufficiently wide knowledge of either the natural phenomena involved or the particular engineering activities. On site assessments by persons with experience in coral reef environments and properly qualified to give reliable objective advice are essential.

7. RECOMMENDATIONS

7.1 Short Term

Management of Spoil Dump

As far as possible disturbance to the spoil dump should be avoided to minimise the release of silt onto the reef. Any excavations in it , particularly ones which open to the sea, should be carefully executed, properly supervised and, if necessary, their effects monitored.

Rubble left on the face of the spoil dump beach may be removed and used to protect erosion-prone areas near the jetty and the helipad. Care should be taken not to disturb the material underlying the beach sediments particularly near the jetty where there is a high proportion of silt present. Rubble removal and placement should normally be undertaken when no waves are breaking on or close to the affected areas.

Vegetation should be allowed to grow on the spoil dump, particularly on its seaward margin, to make the area more visually attractive and to allow wind blown sand to accumulate. In this way tourist use of the area may be enhanced and nesting areas provided for some bird species.

Monitoring of the Spoil Dump

Daily visual observations of waves, erosion and silt plumes, etc., as described in this report, should be continued for at least three years both to verify that conditions have reached some kind of equilibrium under normal wave action and to record the effects of any severe events which may disturb that equilibrium.

The spoil dump should be resurveyed at approximately twelve month intervals and after any severe events which cause significant changes to it. Additional survey control is required at the eastern end of the spoil dump.

Monitoring of the Reef Flat

Reef flat sediments should be sampled after any severe event. Monitoring programmes for reef flat biota should be maintained so that the impact of any severe event can be determined.

7.2 Long Term

Neutralisation of Fine Material in Spoil Dump

In the long term primary concern should be to neutralise the fine material stored within the spoil dump since actual physical removal of the spoil dump from the reef is clearly an impractical solution which could cause worse trouble in its execution.

Specific research is required into the lithification processes occurring in coral cay beaches, including the mechanisms for formation of beach rock and the factors which produce its cementing agents. Action can then be taken to simulate the required conditions within the spoil dump so as to produce and/or accelerate lithification of the fine material.

Reef-top Hydrodynamics

Measurements of tidal and wind-induced currents around the island would give a much clearer understanding of reef-top circulation, the movement of sediment plumes and the location of potential silt deposition regions. However, extensive field measurements on Heron Island Reef are likely to be expensive as well as difficult and possibly dangerous to make under a sufficiently wide range of conditions. Hence it would be more practical to use numerical modelling with a limited number of field measurements, sufficient for calibration and verification of the models.

Refining of the existing numerical cyclone wave prediction model (Gourlay and McMonagle 1989) with a smaller grid to reproduce waves reaching the reef edge and the propagation of cyclonic waves across the reef flat would make it possible to assess the likely effects of cyclonic waves on the spoil dump.

The relationship between wave conditions offshore on either side of the reef and on the reef platform in front of the beach could be established using wave rider buoys and electronic wave staffs.

Hydrographic Survey

There is no comprehensive, reliable survey of the reef flat around Heron Island. AUSLIG or another competent body should be commissioned to make a survey of Heron Reef, west of the lagoon, and of Heron Island as soon as practicable. None of the other investigations of reeftop conditions can be carried out until such a survey is made.

Shoreline Stability

Assessment of the long term stability of the shoreline on the western end of Heron Island and the influence of the boat harbour and other structures could and should be investigated in a large scale physical hydraulic model. The necessary wave conditions for operation of such a model would be derived using the numerical model and field recordings recommended above. No further expansion of the boat harbour or other development on the reef or within the littoral zone of the island should be permitted until their effects can be properly investigated before construction.

Overall stability of Heron Island should be monitored by periodic visual observations including oblique aerial photographs and beach profile measurements at intervals not longer than three to four months. Regular vertical aerial photography and photogrammetry should be undertaken, preferably every two years and definitely every five years, to determine long term changes in the shape of the cay, the volume of sand contained in it, and the development of its vegetation. Parallel monitoring activities should be undertaken of other selected cays in the Capricornia region with lower levels of human interference.

Reef-top Biology

Continuing monitoring of benthic organisms and research concerning reef-top ecology should be undertaken to provide baseline data for Heron Island reef **prior** to any future dredging and to increase general understanding of such communities for application to other reef locations where dredging or other construction works may have to be undertaken in the future.

7.3 General

Application to Other Projects

The fundamental lesson from the Heron Island boat harbour enlargement project is obvious. All dredging or construction projects which involve disturbance to coral reefs need to be carefully planned so as to minimise the release of silt and so avoid its deposition on reefal areas. The execution of projects needs to be carefully supervised and their effects monitored to ensure that operations have complied with the permit conditions.

Recording of Human Activity

Considerable difficulty was experienced during this project in determining when various human activities, such as relocation of rubble along the shoreline or reshaping of the beach or spoil dump, actually occurred. Consequently it is recommended that all persons or organisations which have permits to undertake continuing activities which may affect the portion of a reef or island being monitored should be required to maintain a log book recording the dates of occurrence, the nature and extent of such activities. The log book should be available for inspection by authorised persons and should be forwarded to the Authority for archiving on completion of the project or, in the case of continuing projects, at specified intervals.

8. ACKNOWLEDGEMENTS

A considerable number of persons has given assistance or supplied information relevant to this project.

The project could not have been undertaken without the expertise, enthusiasm and effort of Jennifer Hacker (Civil Engineering Department) and Marshall Butterworth (Geology Department). Much of the field work and most of the laboratory analyses have been carried out by them or under their supervision.

The director of Heron Island Research Station, Dr Ian Lawn, has provided use of facilities and station personnel to assist in the field work. In particular the daily observations of spoil dump conditions have been made, and are continuing to be made, by a number of persons, including Myriam Prekker, Lesley Newman, Andrew Flowers, Elna Anastasiou, Kathy Brundler, Lindy Hayes, Sandra Whittingham, Pippi Lawn and Tim Daley.

Brian Fenn of the Buildings and Grounds section of The University of Queensland provided liaison with the contractor who supplied the backhoe used in excavating test pits in the spoil dump.

Dr Bryan Hacker assisted in the field work on the spoil dump, particularly in making the auger holes.

Myriam Prekker supplied information concerning water temperature on Heron Island reef.

Professor Ted White (Chemical Engineering Department, The University of Queensland) made the laser size analyser available for our use.

Various National Parks and Wildlife Service personnel supplied information and photographs concerning events during and following the boat harbour enlargement works as well as aerial photographs of the spoil dump taken since that time.

Alan Grummitt and Mike Neale (Cullen, Grummit and Roe) supplied information about the boat harbour enlargement works.

John Broadbent and Ray Peddersen of the Department of Harbours and Marine provided analyses of tides at Heron Island. They also arranged for the supply of a tide board.

Dr Rod Rodgers (Botany Department, The University of Queensland) identified the various plant species growing on the spoil dump.

The Manager of Heron Island Resort agreed to the installation of the tide board on one of the jetty piles and made equipment available for doing this.

The text of this report was prepared in the Department of Civil Engineering of The University of Queensland by Ann Sellars. The figures were drawn by Reg Stonard (Department of Civil Engineering) and Elvira Burdin (Department of Geology and Mineralogy).

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PHOTOGRAPHS

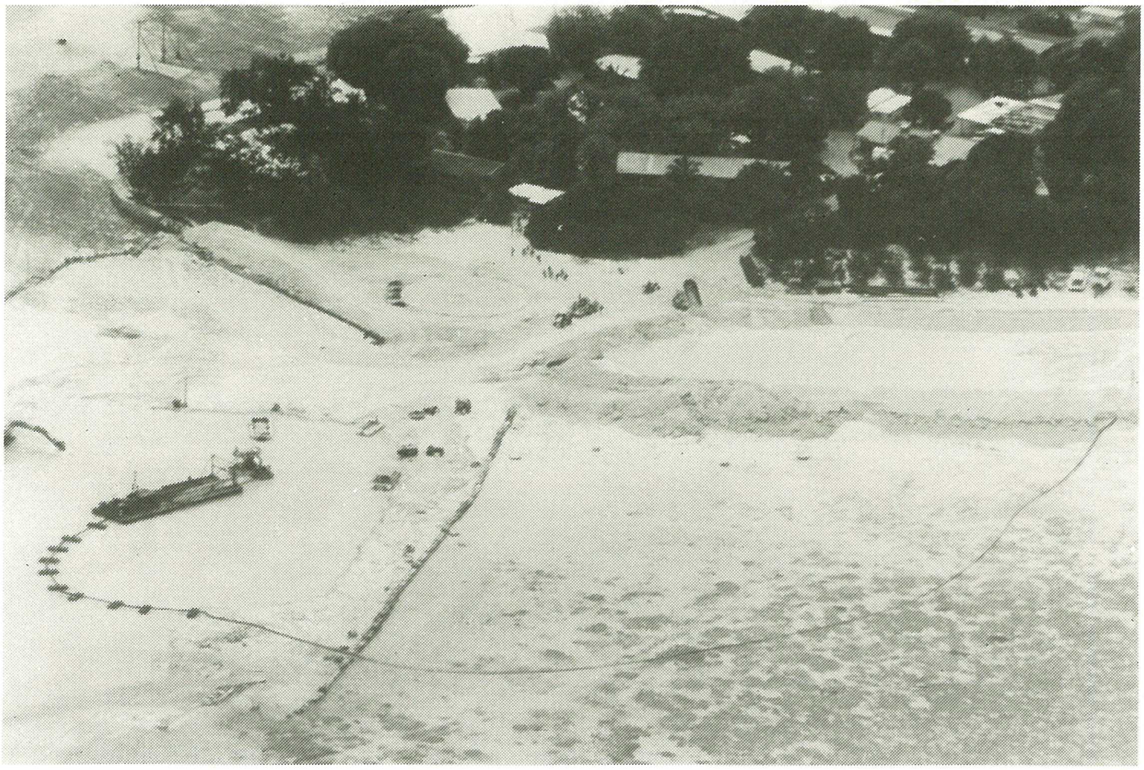


Photo 1. Aerial view of boat harbour and spoil dump during construction - 6 October 1987. (Photo QNPWS)

Photo 2. Aerial view of completed spoil dump showing silt plume moving southeastwards along shoreline - November 1987. (Photo QNPWS)

Photo 3. Overflow from settling pond during early stage of dredging - 18(?) September 1987. (Photo Alan Smith)

Photo 4. Overflow from settling pond/spoil dump during late stage of dredging - 28-29 (?) October 1987 (Photo Alan Smith)

Photo 5. Aerial view of spoil dump shortly after completion of boat harbour construction - 7 December 1987 (Photo QNPWS)

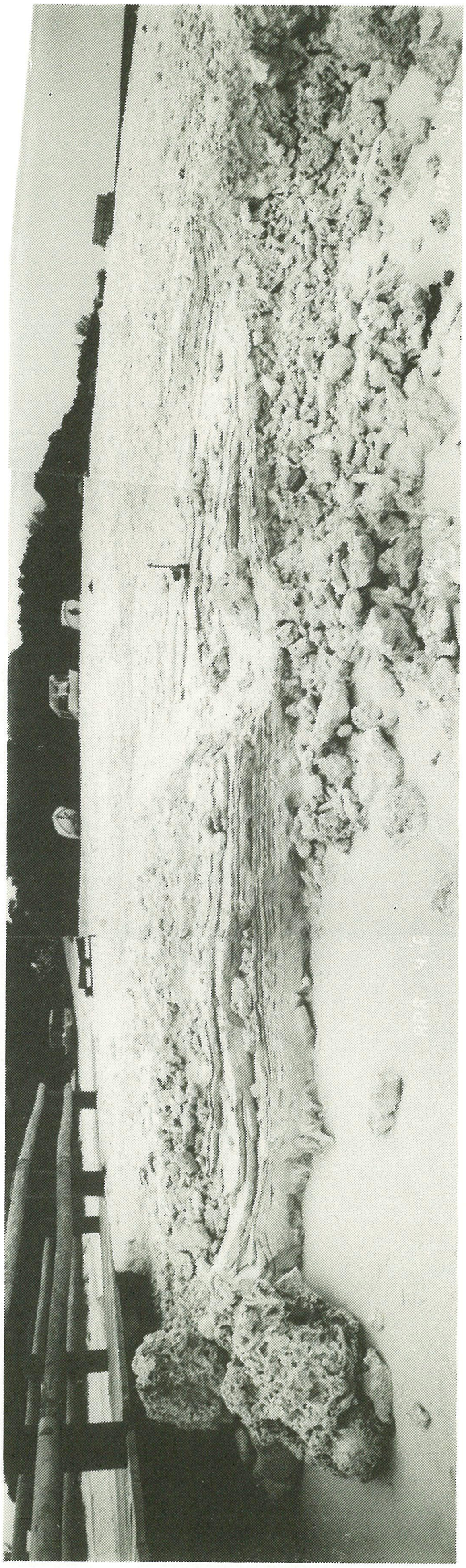


Photo 6. Silt scarp and spoil dump beach south of jetty in vicinity of station 2 - 4 April 1989. (Photo J.L.F. Hacker)

Photo 7. Erosion scarp and shingle on beach face at southern end of spoil dump in vicinity of station 1 - 16 December 1988 (Photo J.S. Jell)

Photo 8. Interbedded layers of silt, sand and coarser material in vicinity of station 1 - 16 December 1988 (Photo J.S. Jell)

Photo 9. Waves breaking on spoil dump and creating a silt plume - 6 April 1989. (Photo J.L.F. Hacker)

Photo 10. Silt plume generated from spoil dump beach - 6 April 1989. (Photo J.L.F. Hacker)

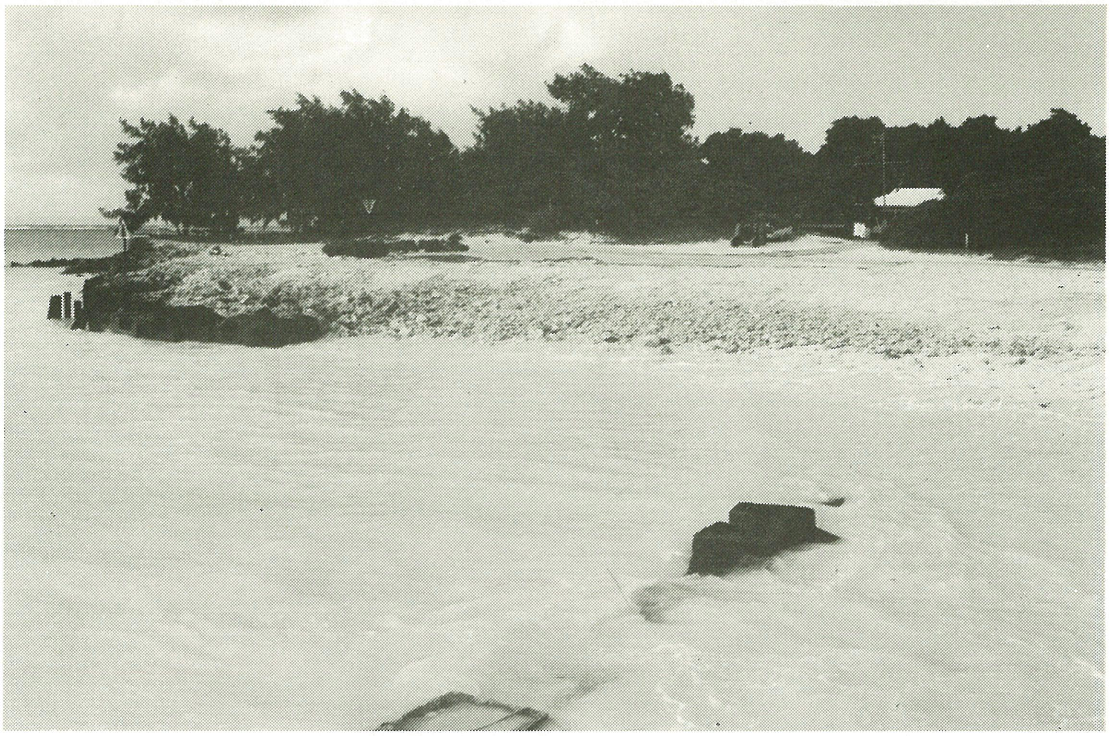


Photo 11. Silt plume north of jetty following wave attack and mechanical movement of beach material to protect jetty - 29 May 1989. (Photo Andrew Flowers)

Photo 12. Localised silt plume generated by excavator working in boat harbour - 19 February 1988. (Photo QNPWS)

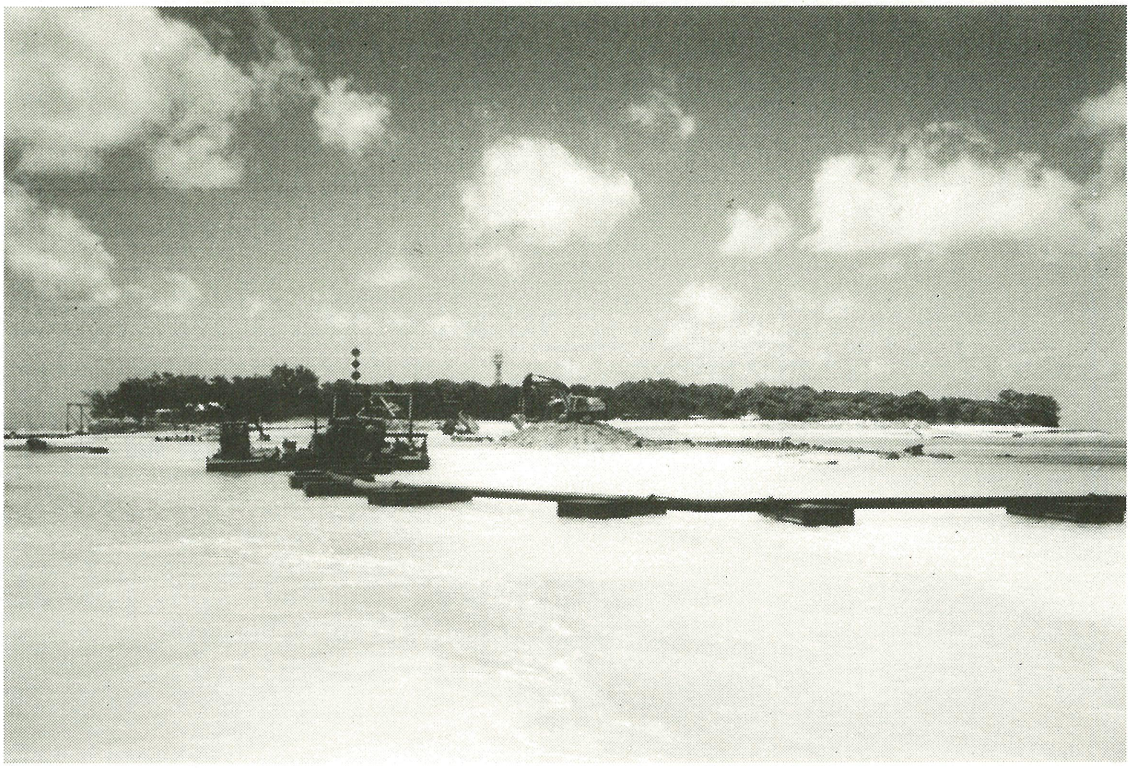


Photo 13. Silt plume generated by dredge working in boat harbour - 21 September 1987. (Photo QNPWS)

Photo 14. Silt plumes from dredge and spoil dump extending over southern reef flat - 23 October 1987. (Photo QNPWS)

Photo 15. Silt-covered beach rock on southern side of island - 10 March 1988. (Photo QNPWS)

Photo 16. Western end of beach rock near spoil dump showing silt remaining on lower levels of rock - 1 December 1990. (Photo J.S. Jell)

Photo 17. Dried algae-encrusted mud on beach rock - May 1988.
(Photo J.S. Jell)

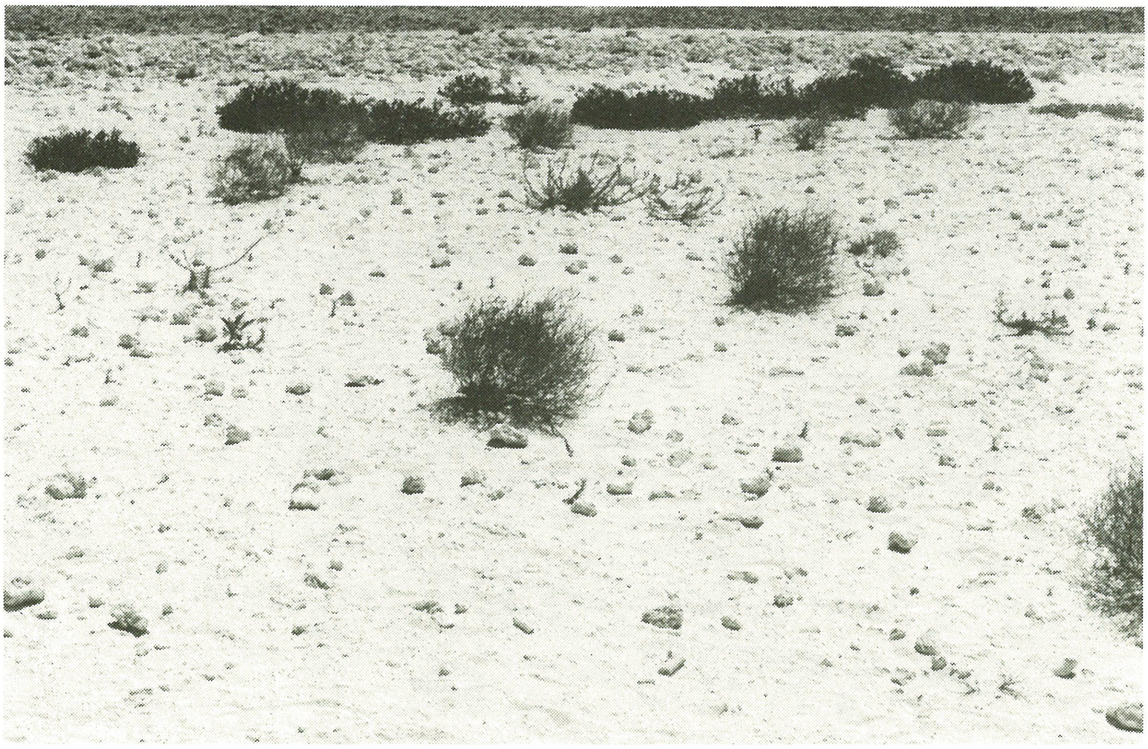


Photo 18. Vegetation on spoil dump - 1 December 1990 (Photo J.S. Jell)

FIGURES

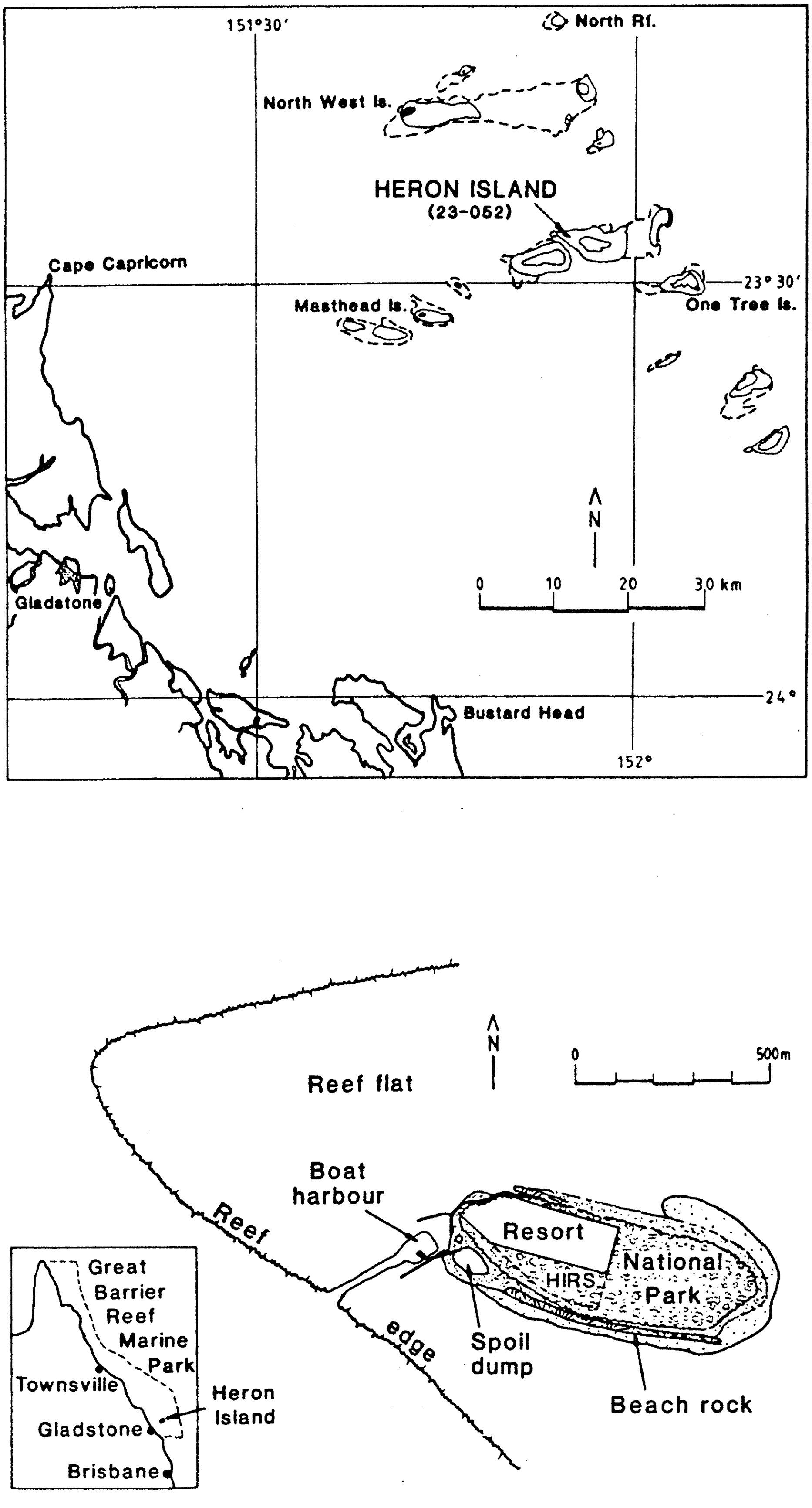


Figure 1. Location of Heron Island

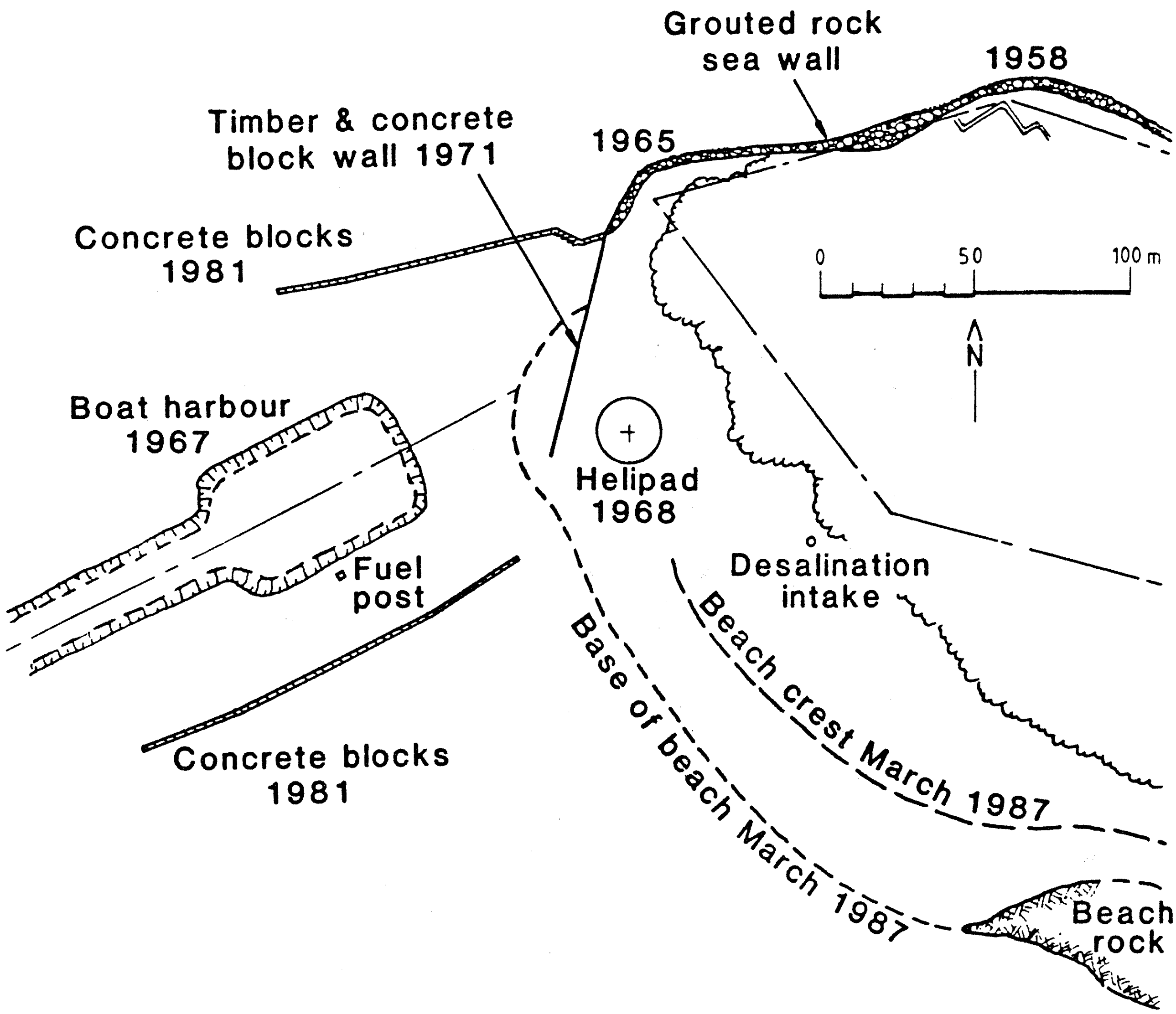


Figure 2. Western end of Heron Island - Works constructed prior to 1987

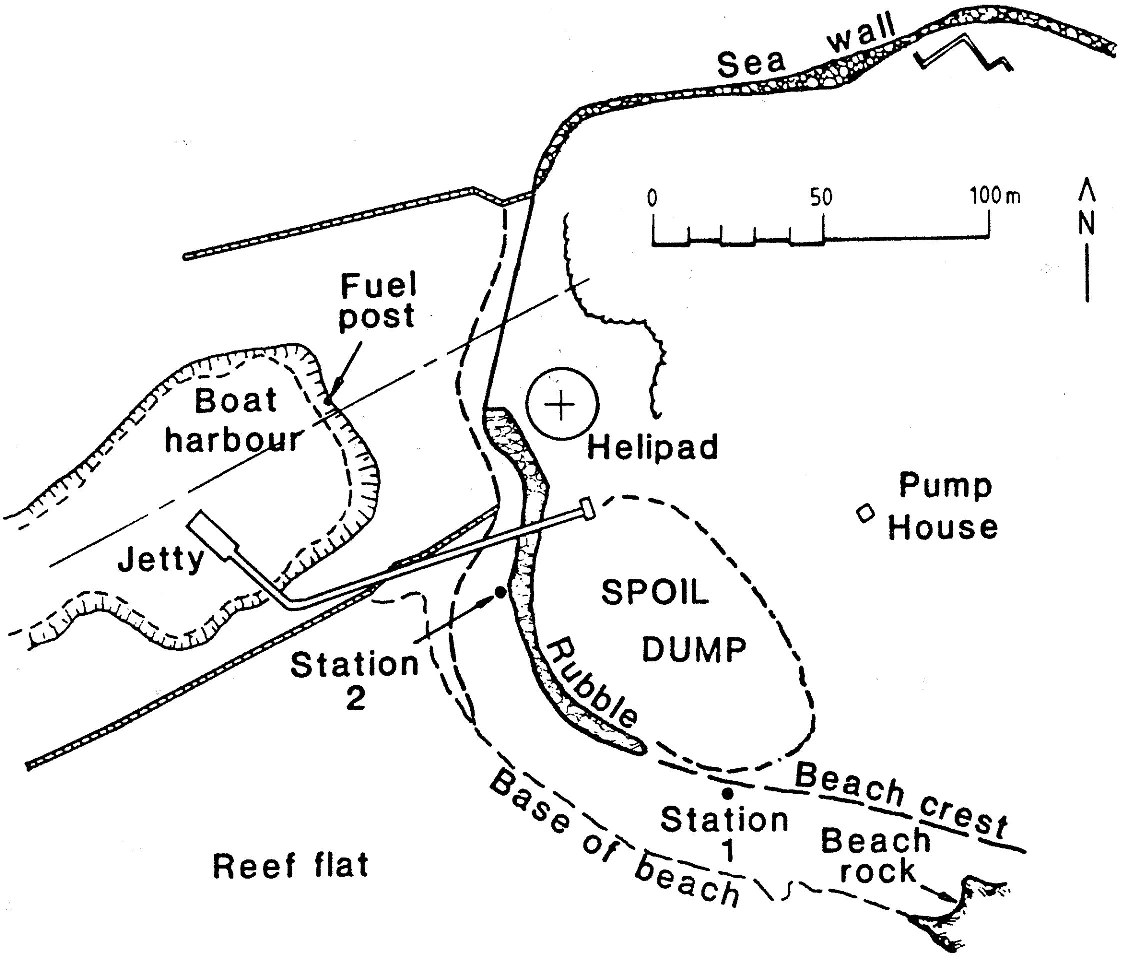


Figure 3. Boat Harbour Enlargement Works 1987

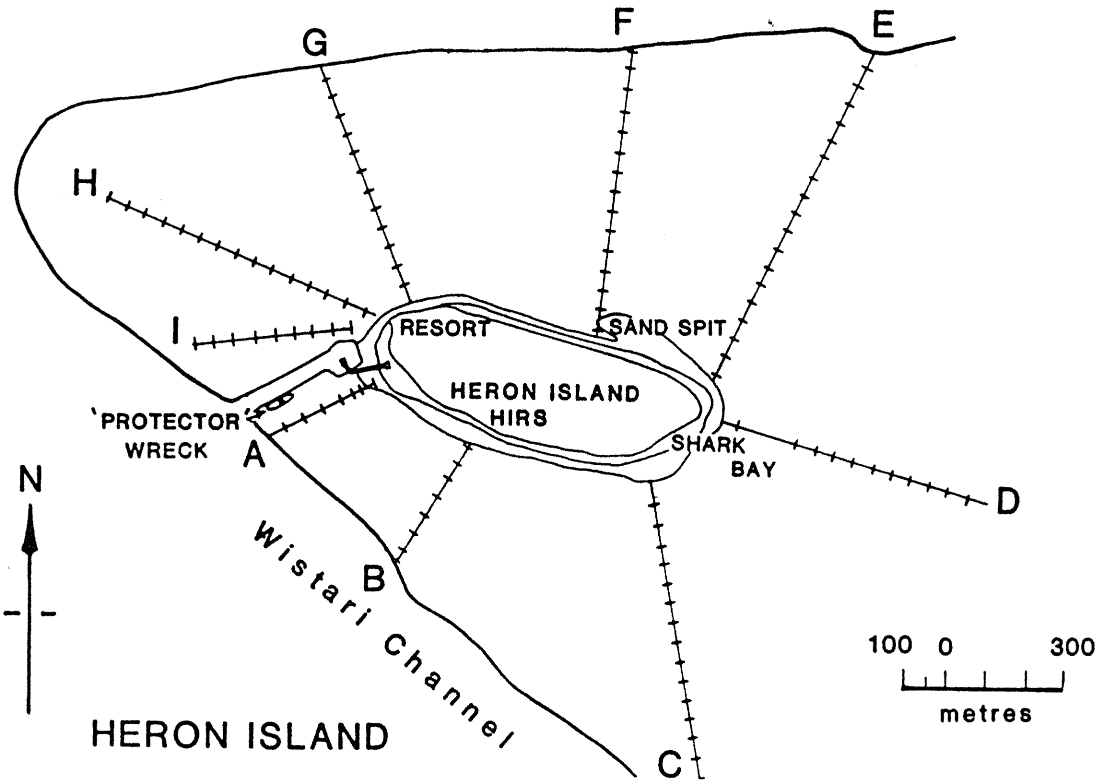


Figure 4. Location of sediment sampling traverses

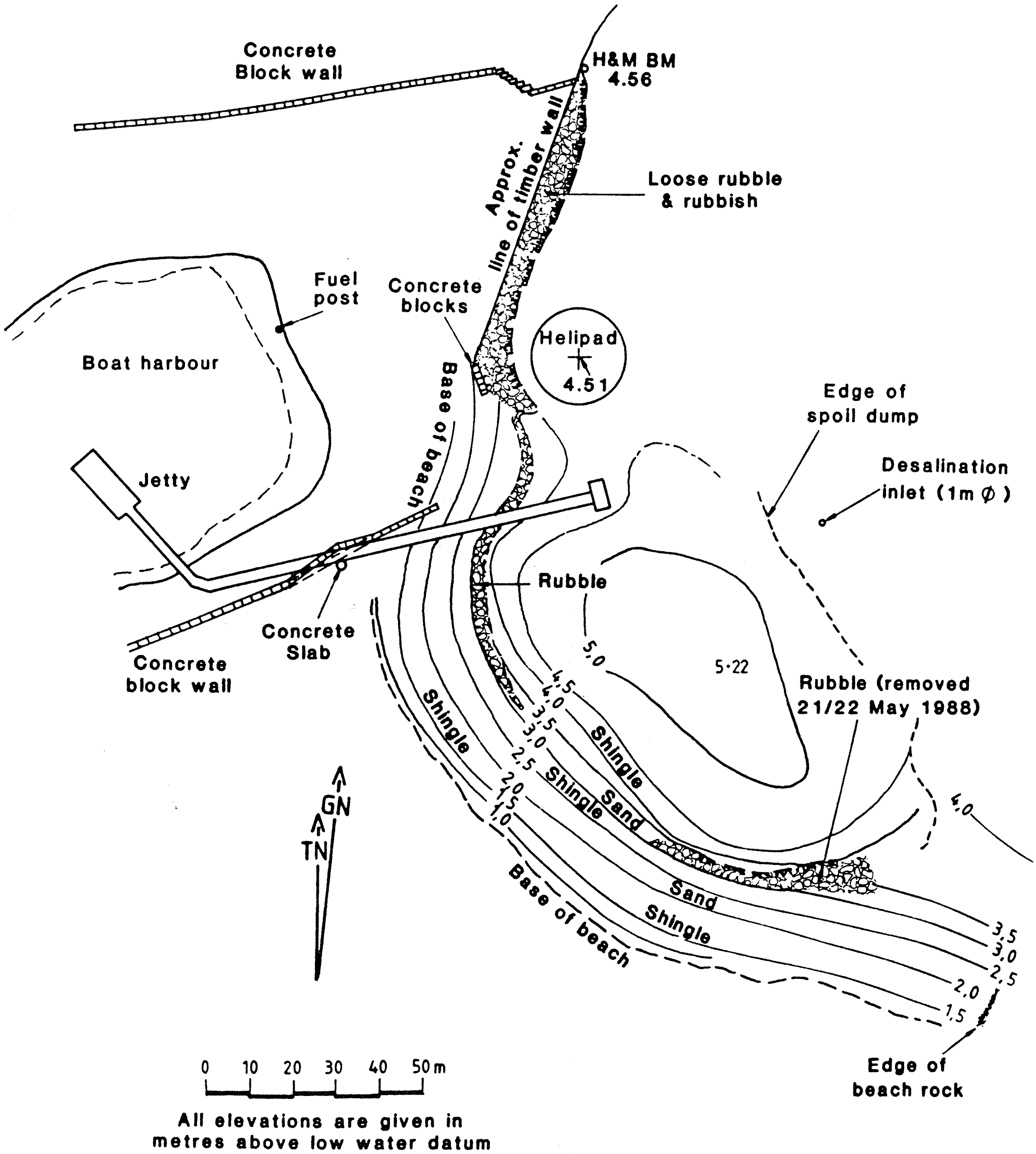


Figure 5. Spoil dump - May 1988

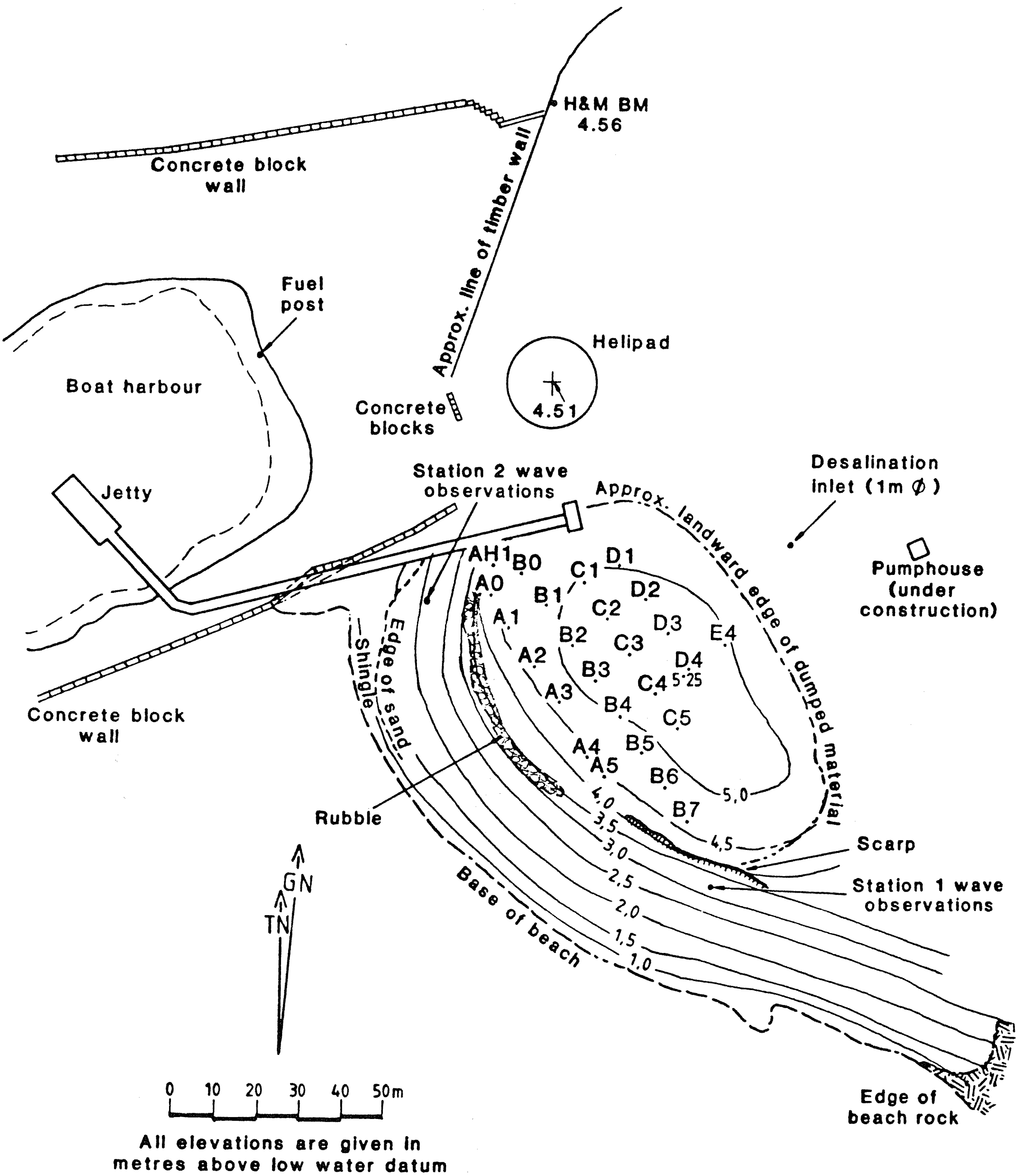


Figure 6. Spoil dump - April 1989 including location of test holes

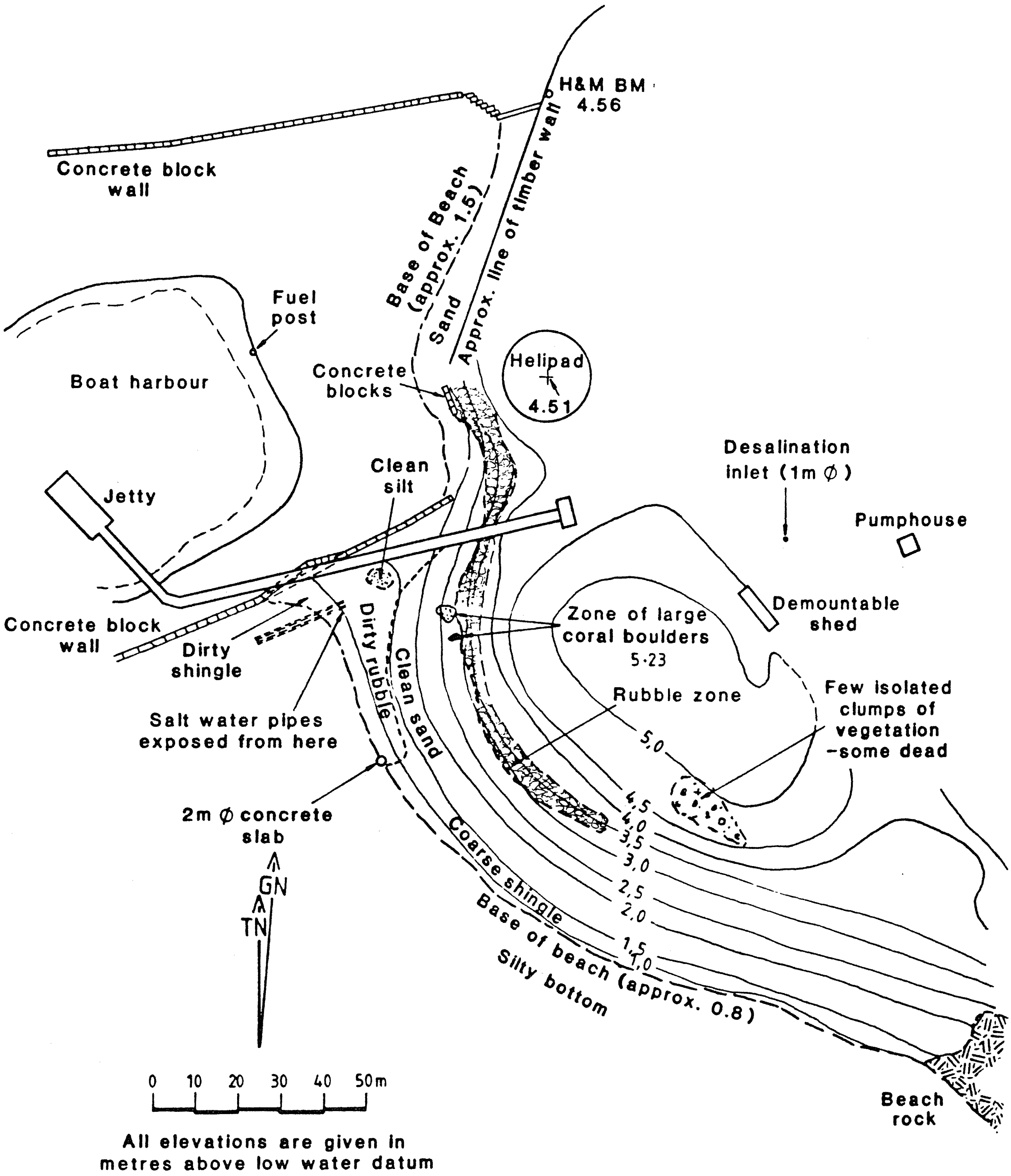


Figure 7. Spoil dump - January 1990

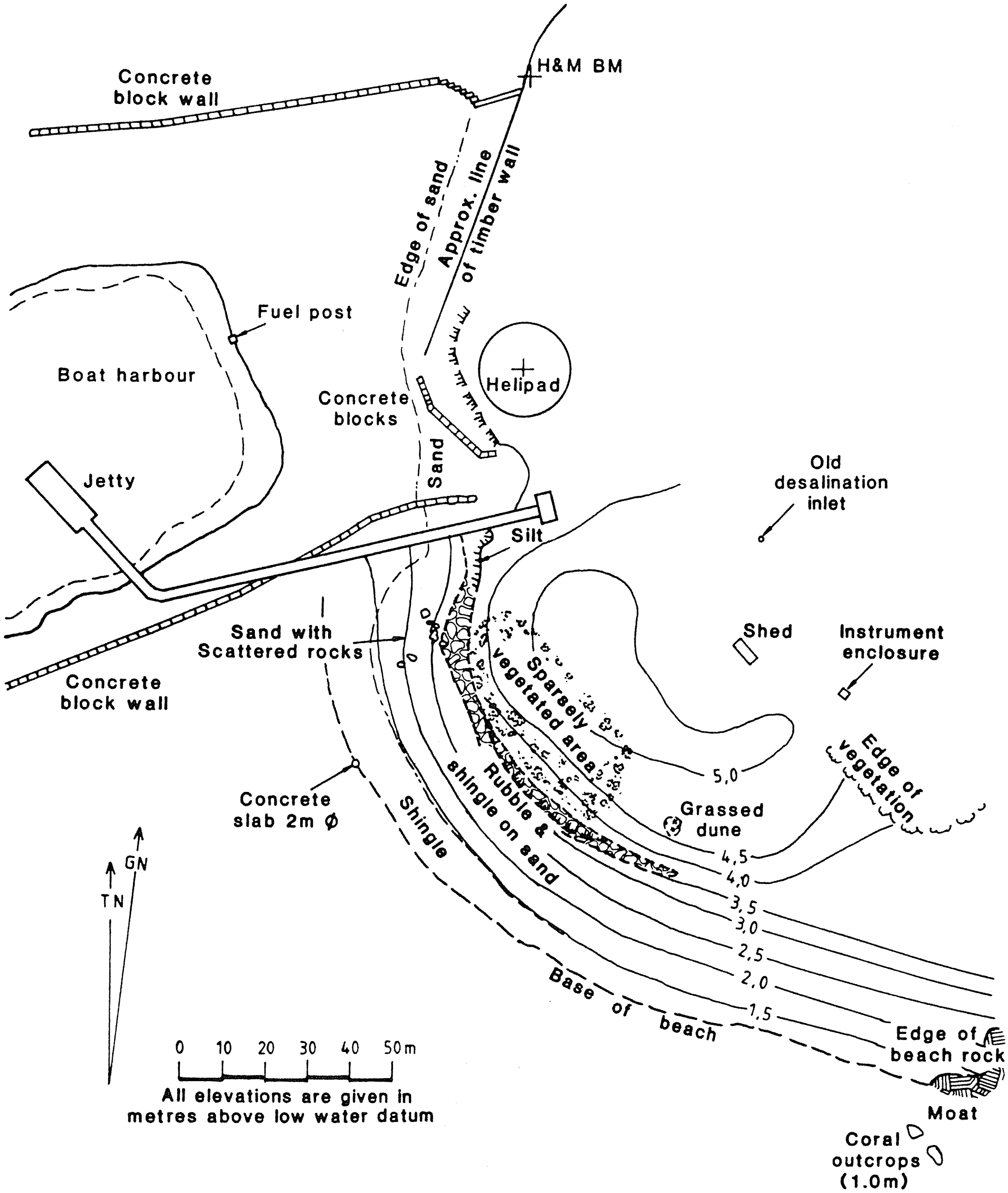


Figure 8. Spoil dump - June 1991

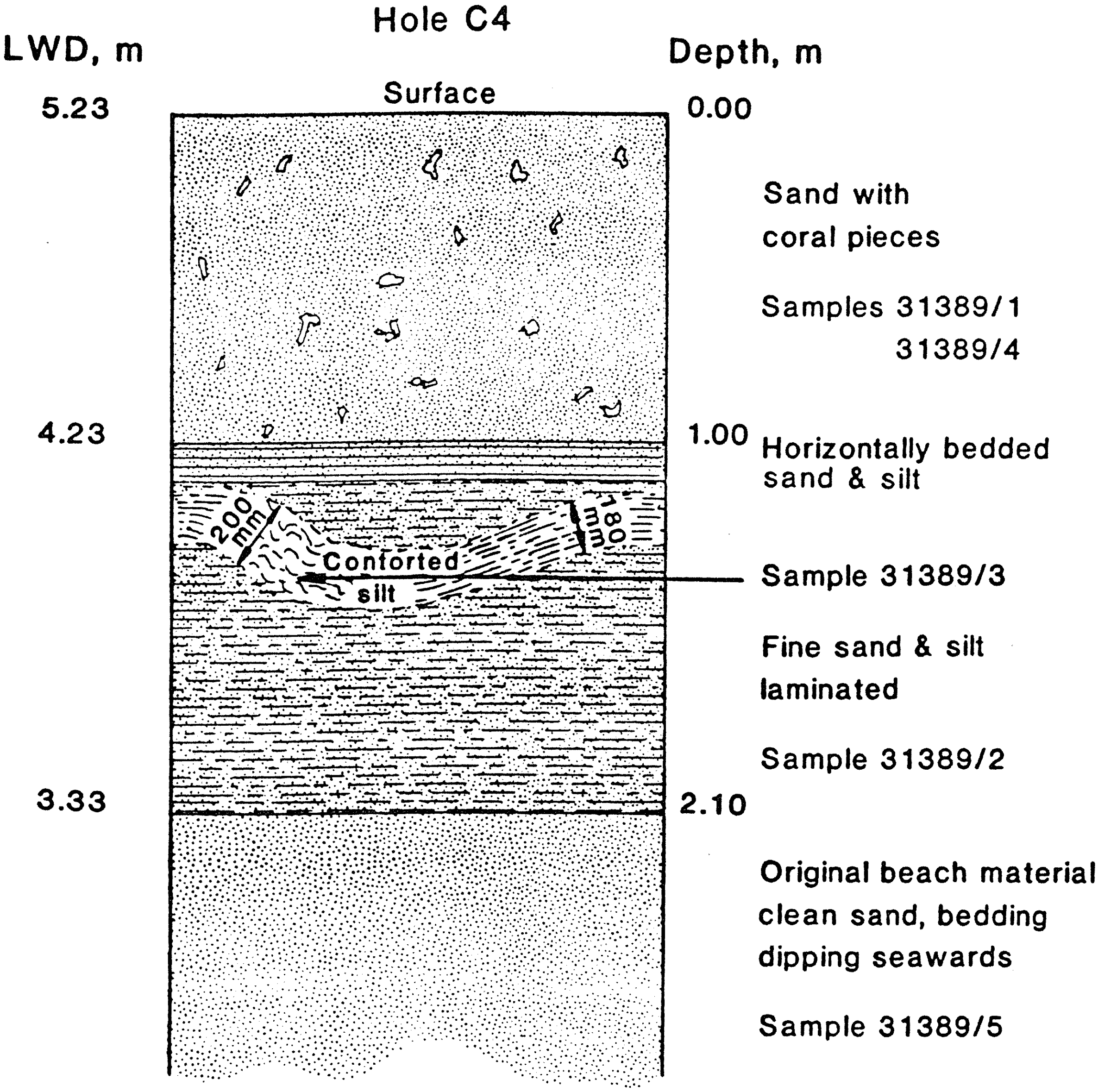


Figure 9. Profile in excavation at location C4

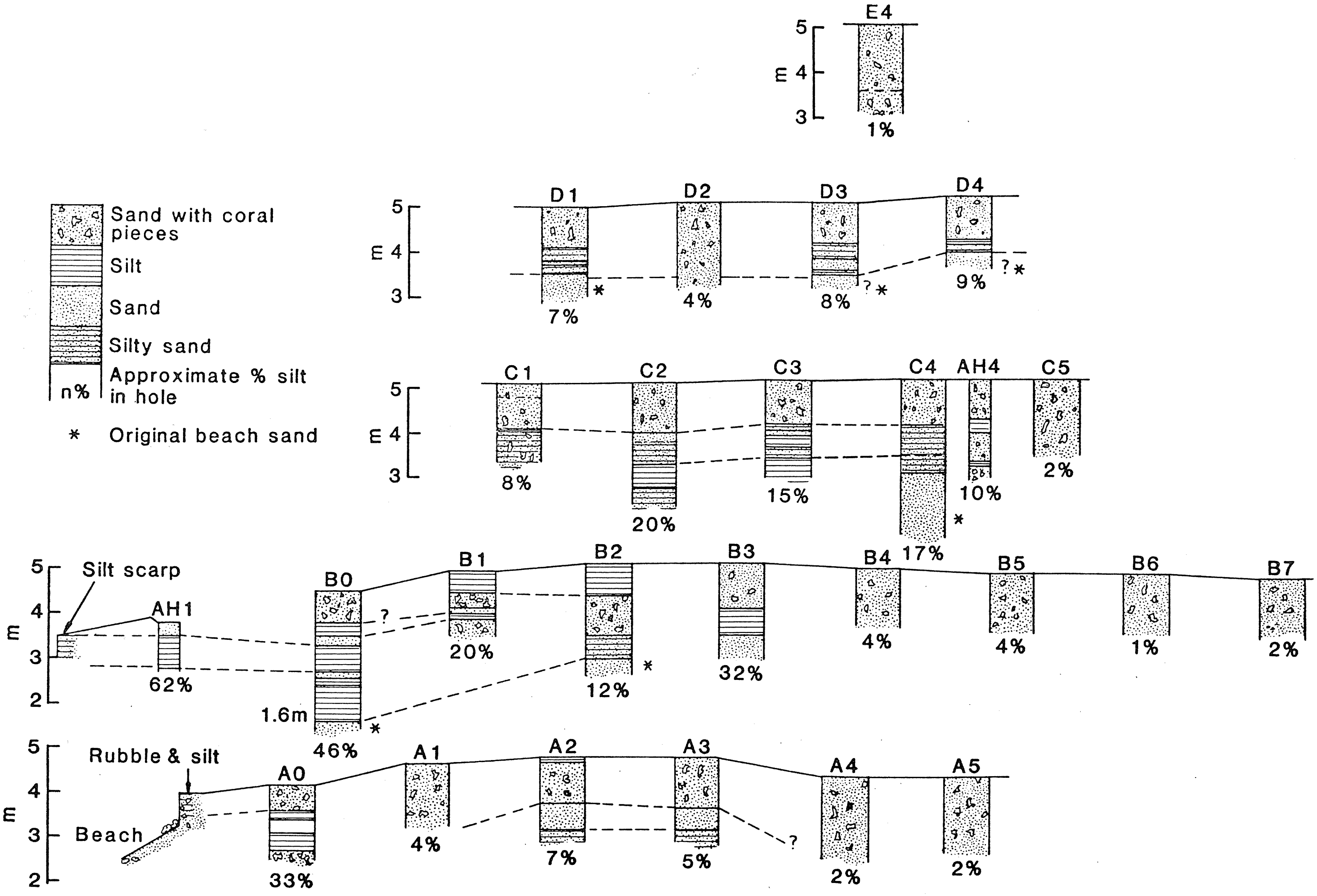


Figure 10. Sections through spoil dump along borehole grid lines

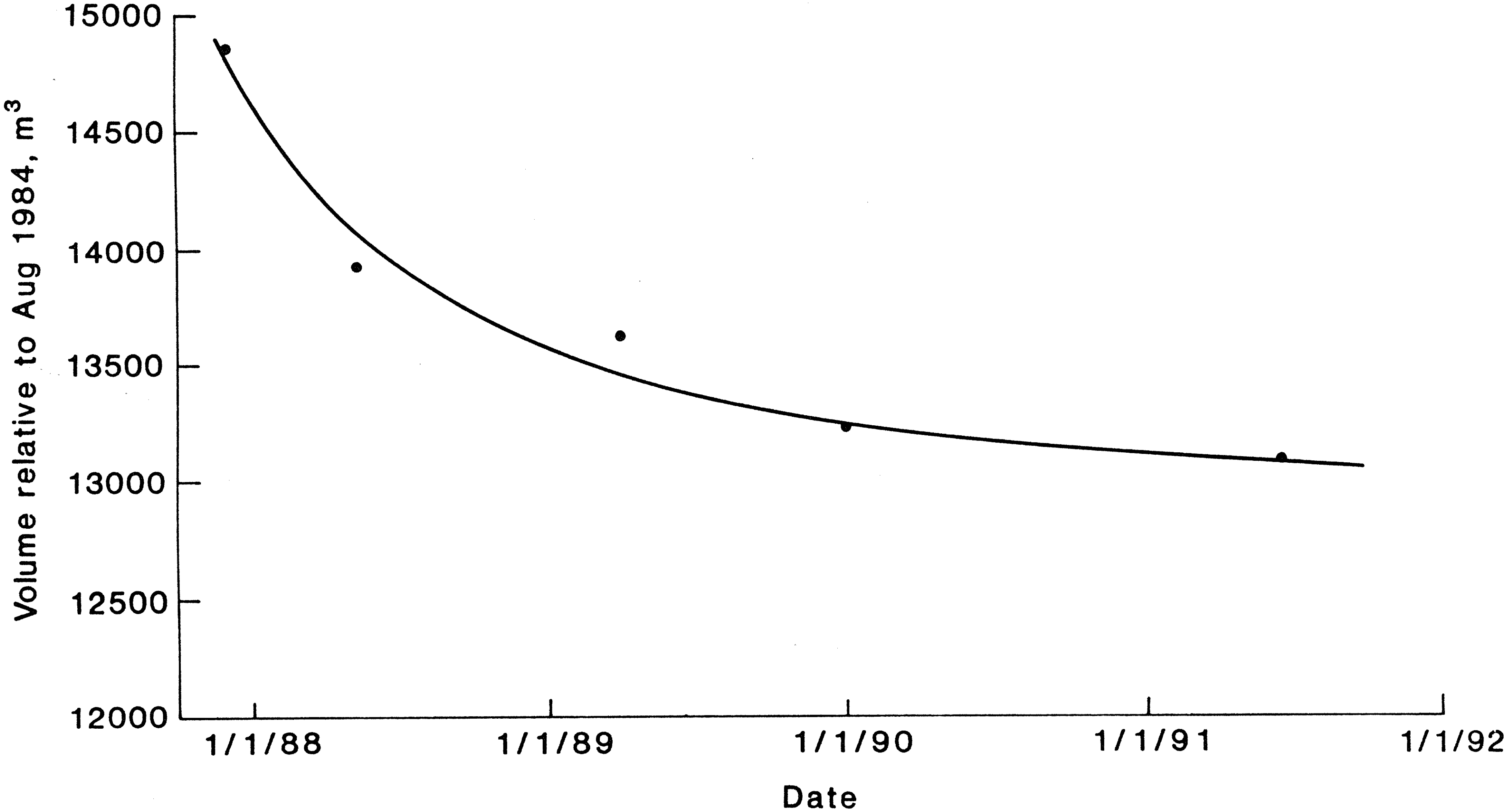


Figure 11. Change in spoil dump volume - December 1987 to June 1991

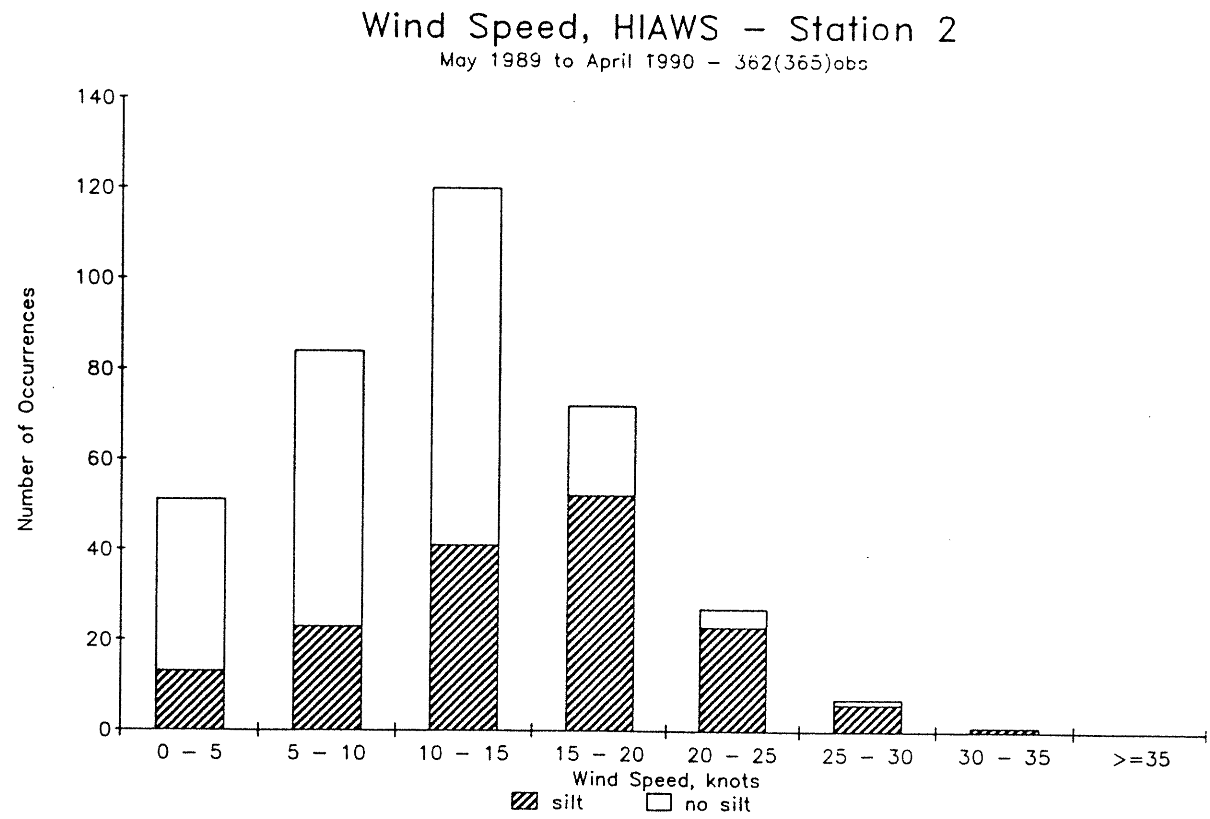


Figure 12. Silt plume occurrences and wind speed - station 2
May 1989 - April 1990

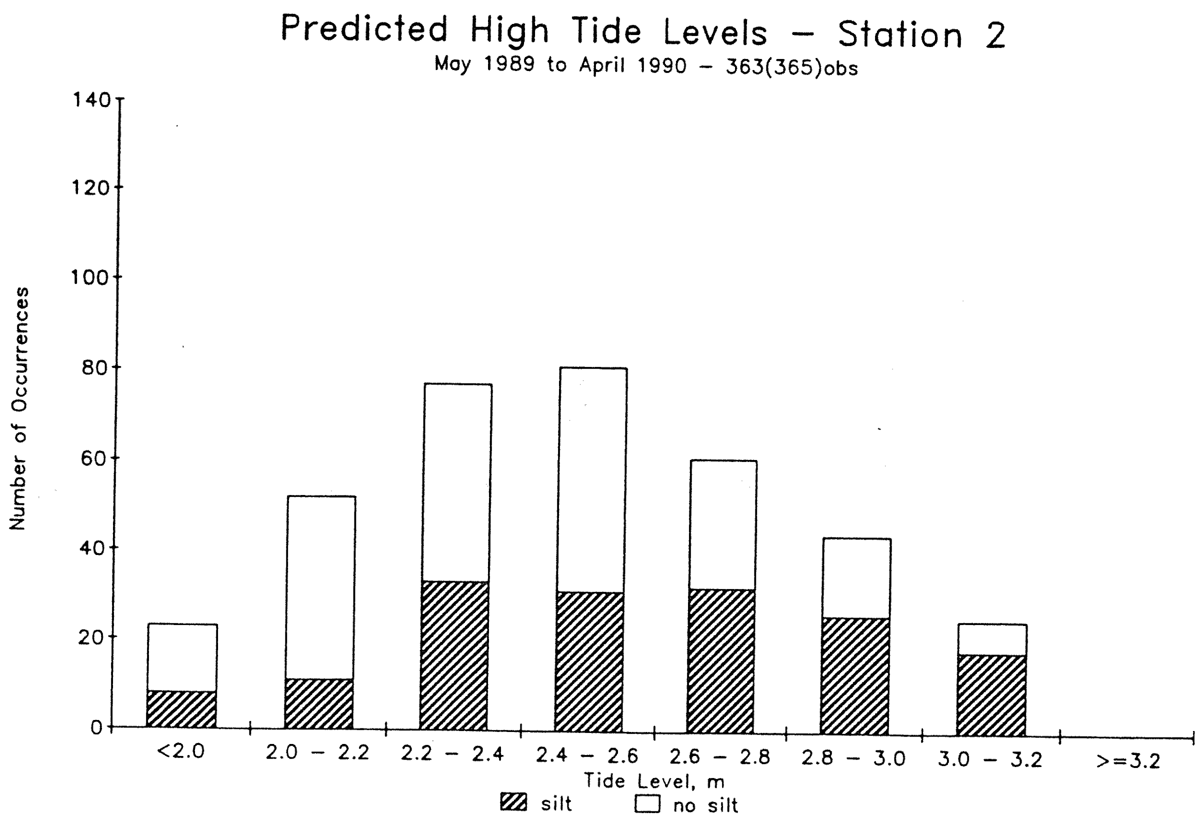


Figure 13. Silt plume occurrences and high tide level - station 2
May 1989 - April 1990

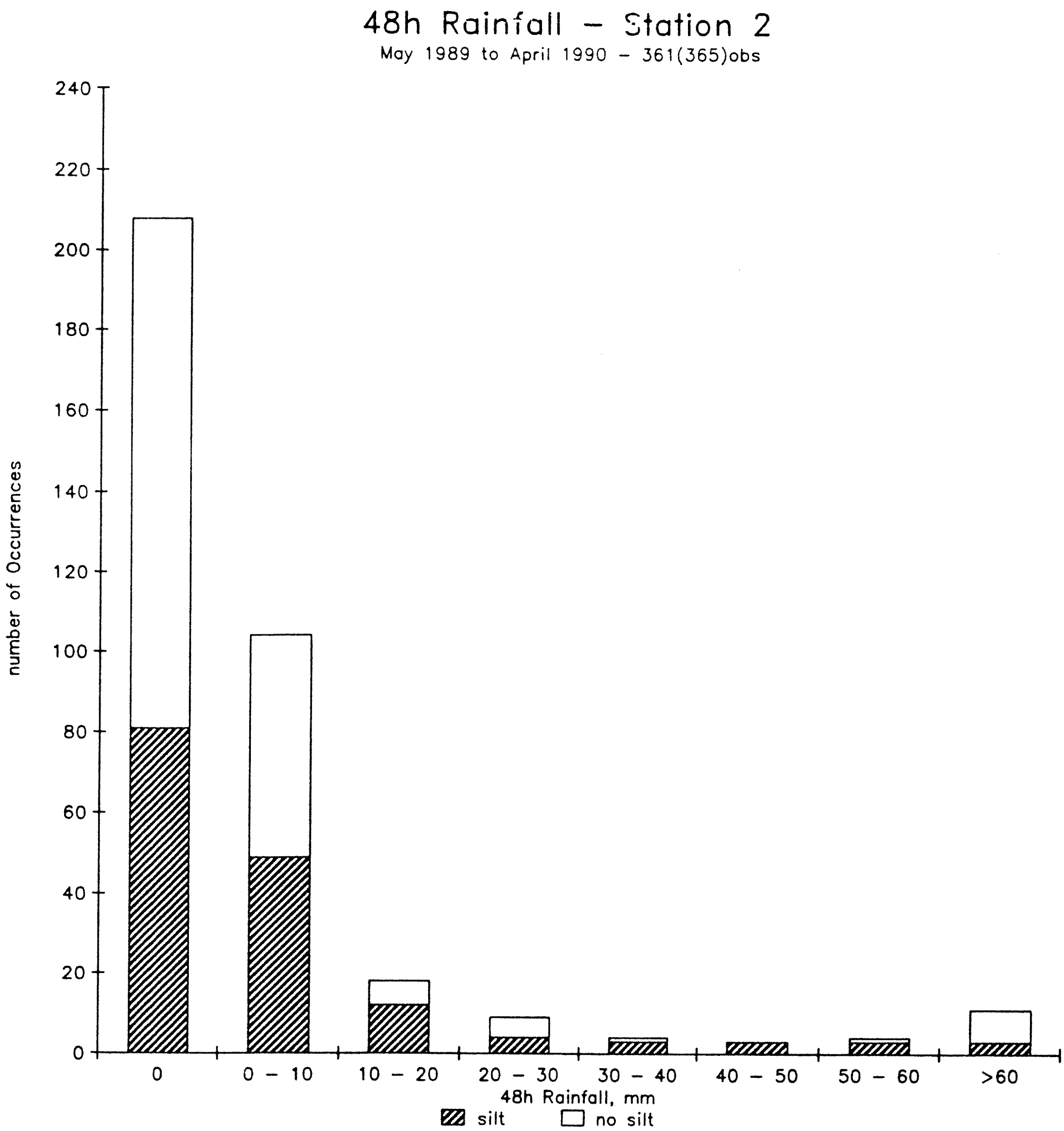


Figure 14. Silt plume occurrences and 48h rainfall - station 2
May 1989 - April 1990

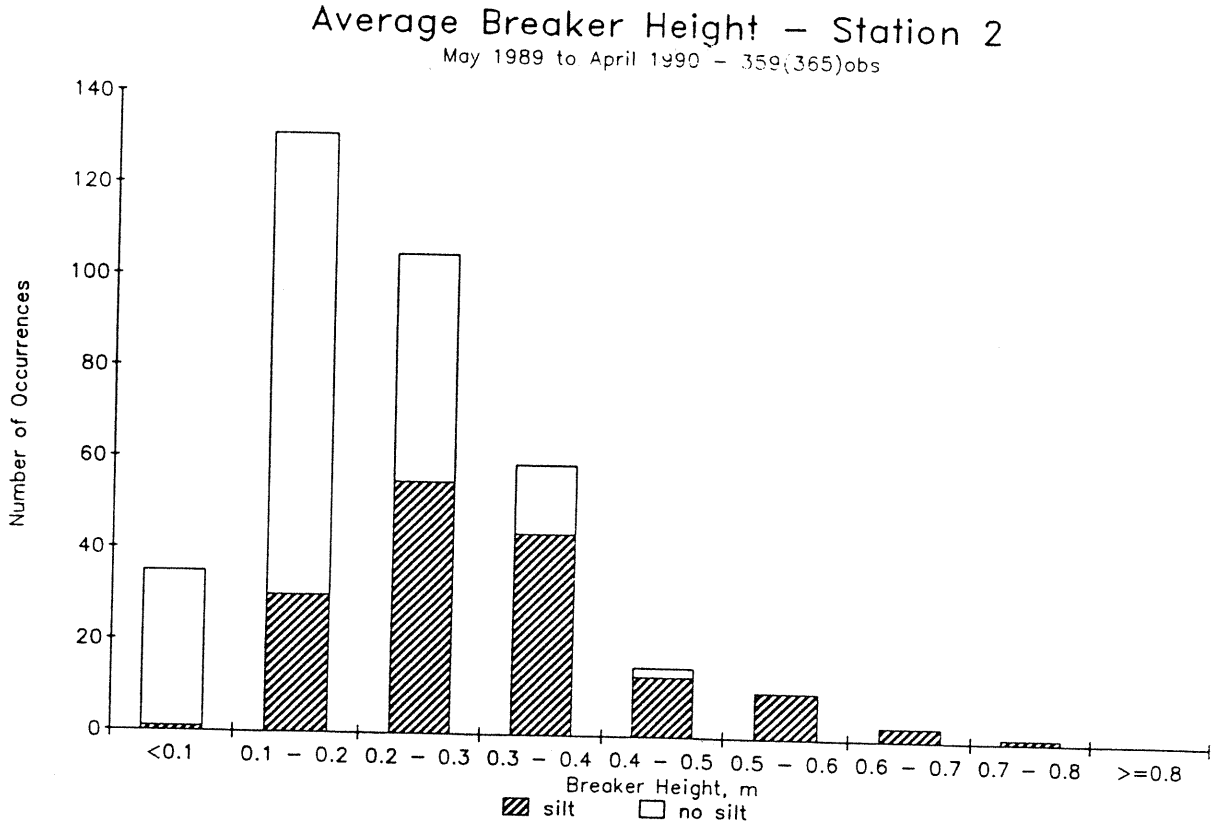


Figure 15. Silt plume occurrences and average breaker height - station 2
May 1989 - April 1990

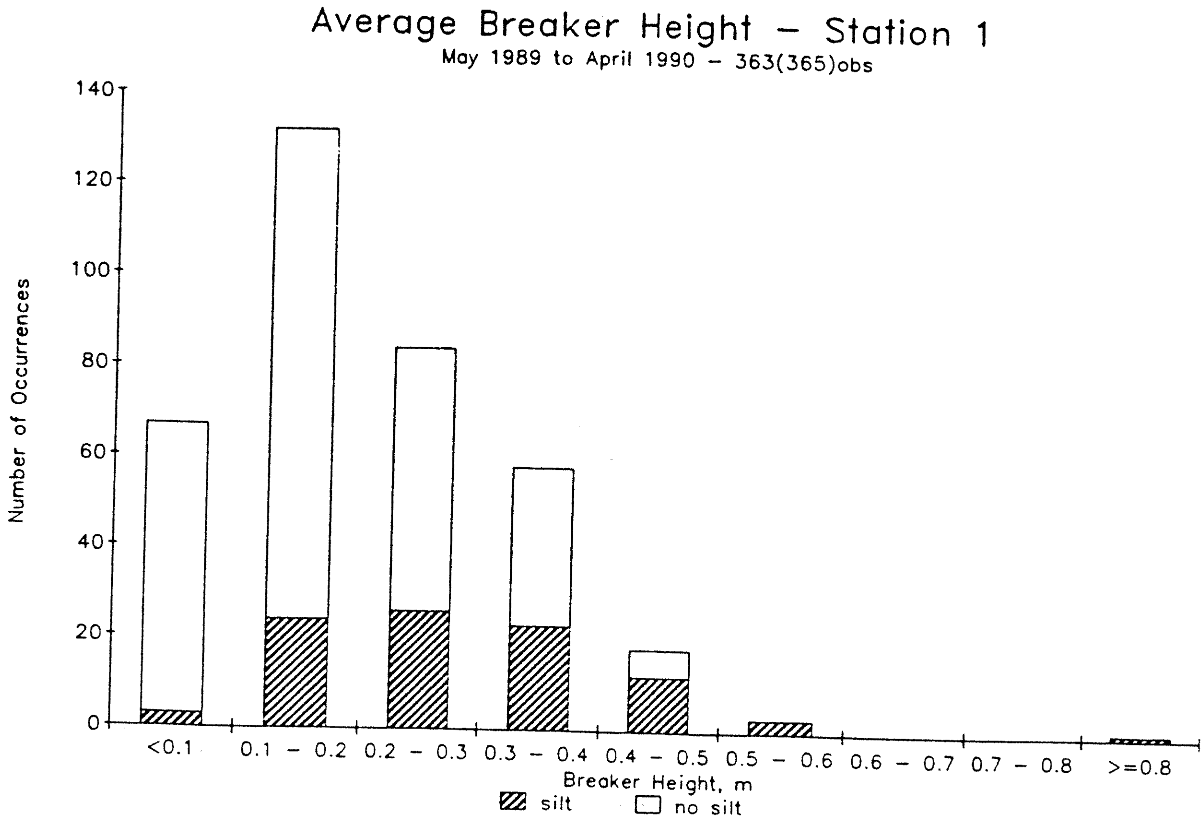


Figure 16. Silt plume occurrences and average breaker height - station 1
May 1989 - April 1990

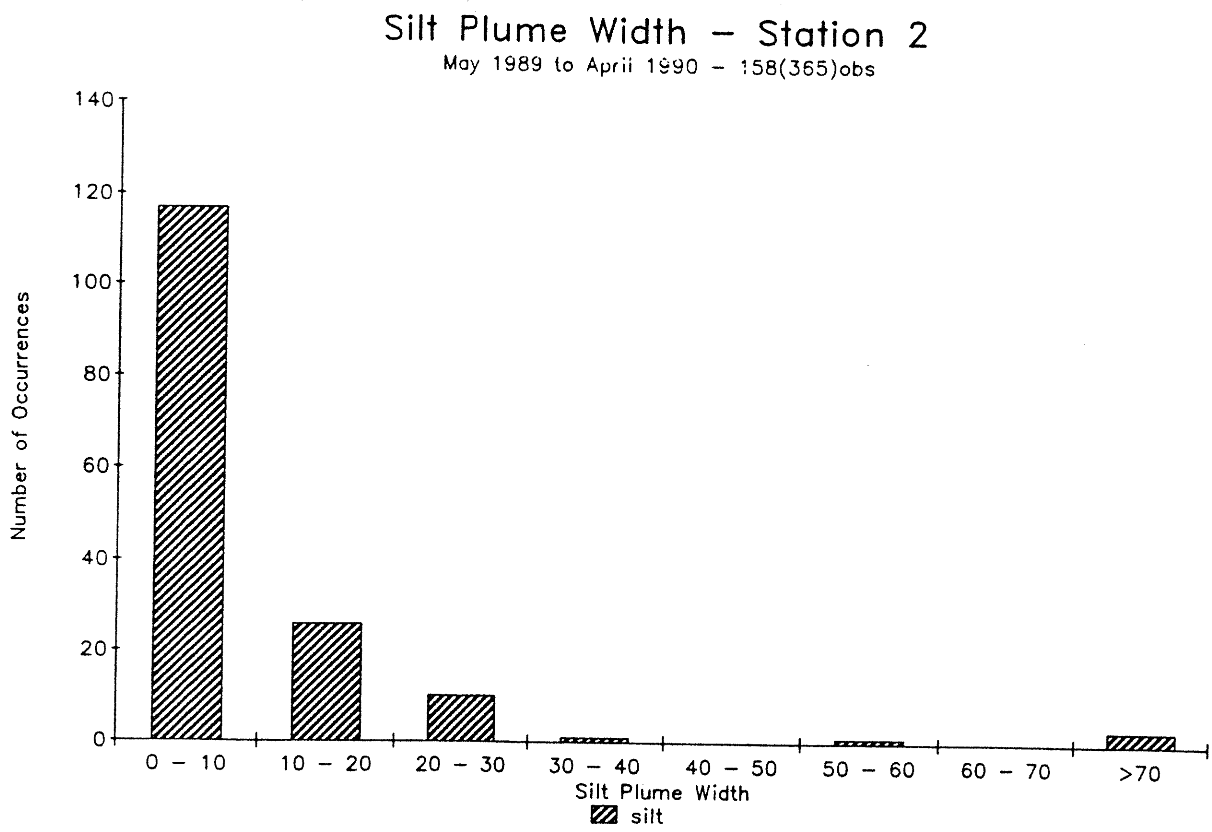


Figure 17. Silt plume widths at station 2
May 1989 - April 1990

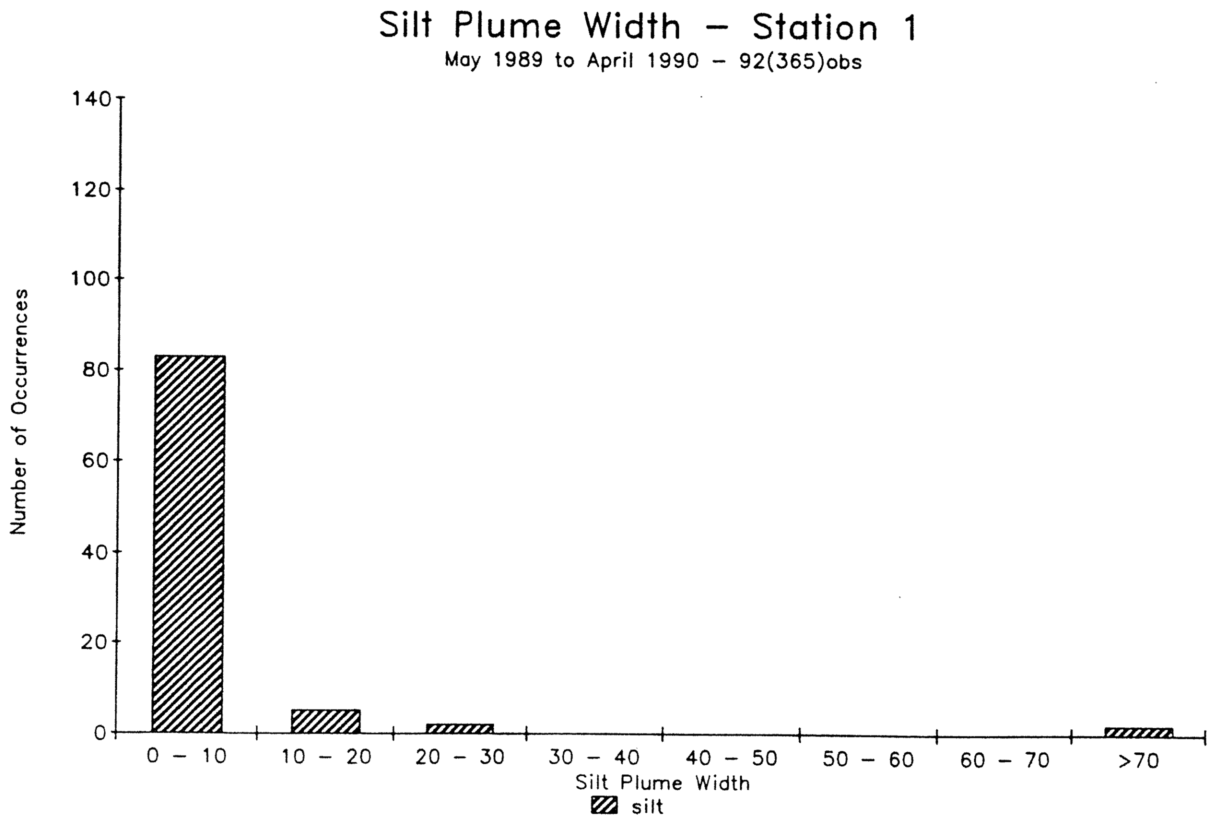


Figure 18. Silt plume widths at station 1
May 1989 - April 1990

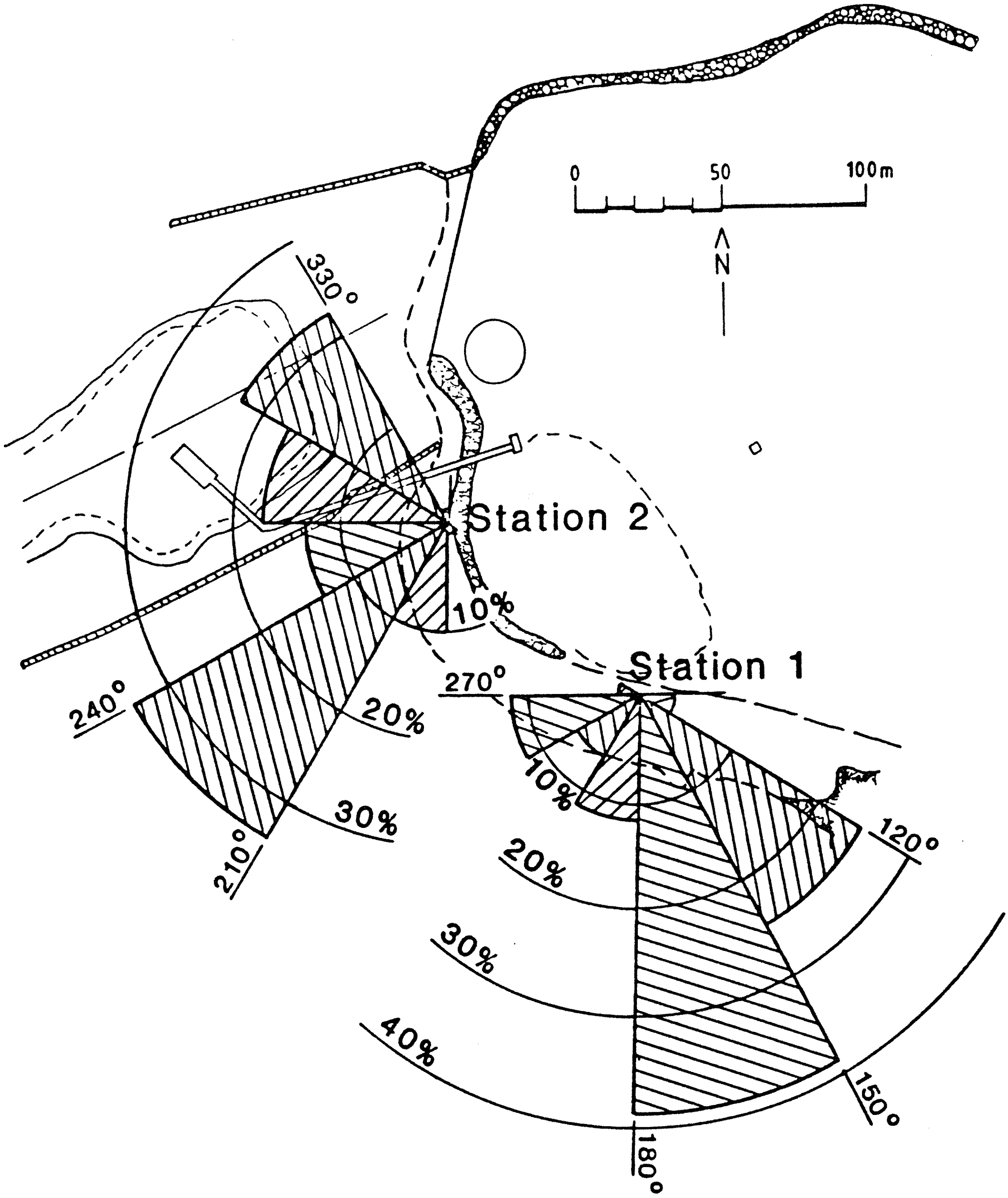


Figure 19. Wave directions at spoil dump
May 1989 - April 1990

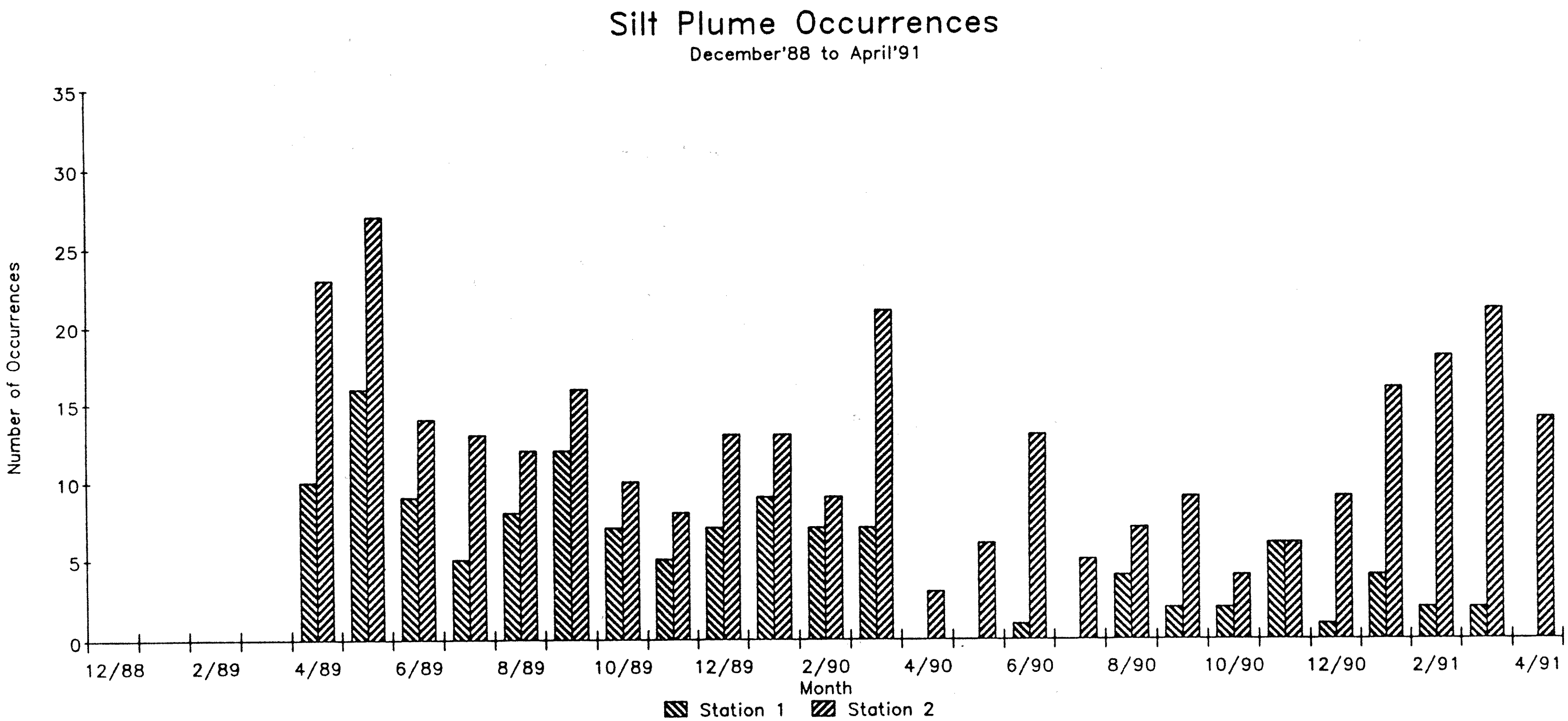


Figure 20. Monthly silt plume occurrences - December 1988 to April 1990

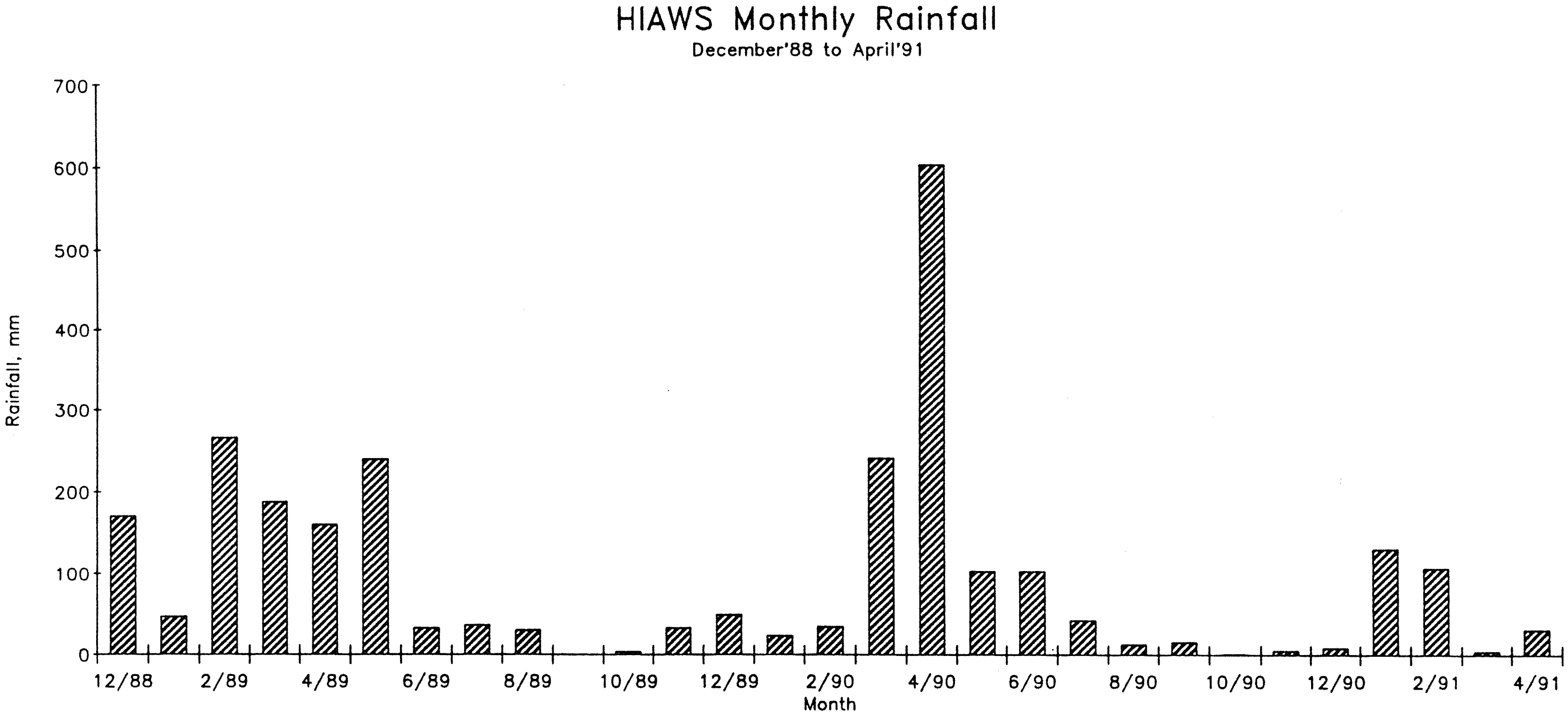


Figure 21. Monthly rainfall - December 1988 to April 1990

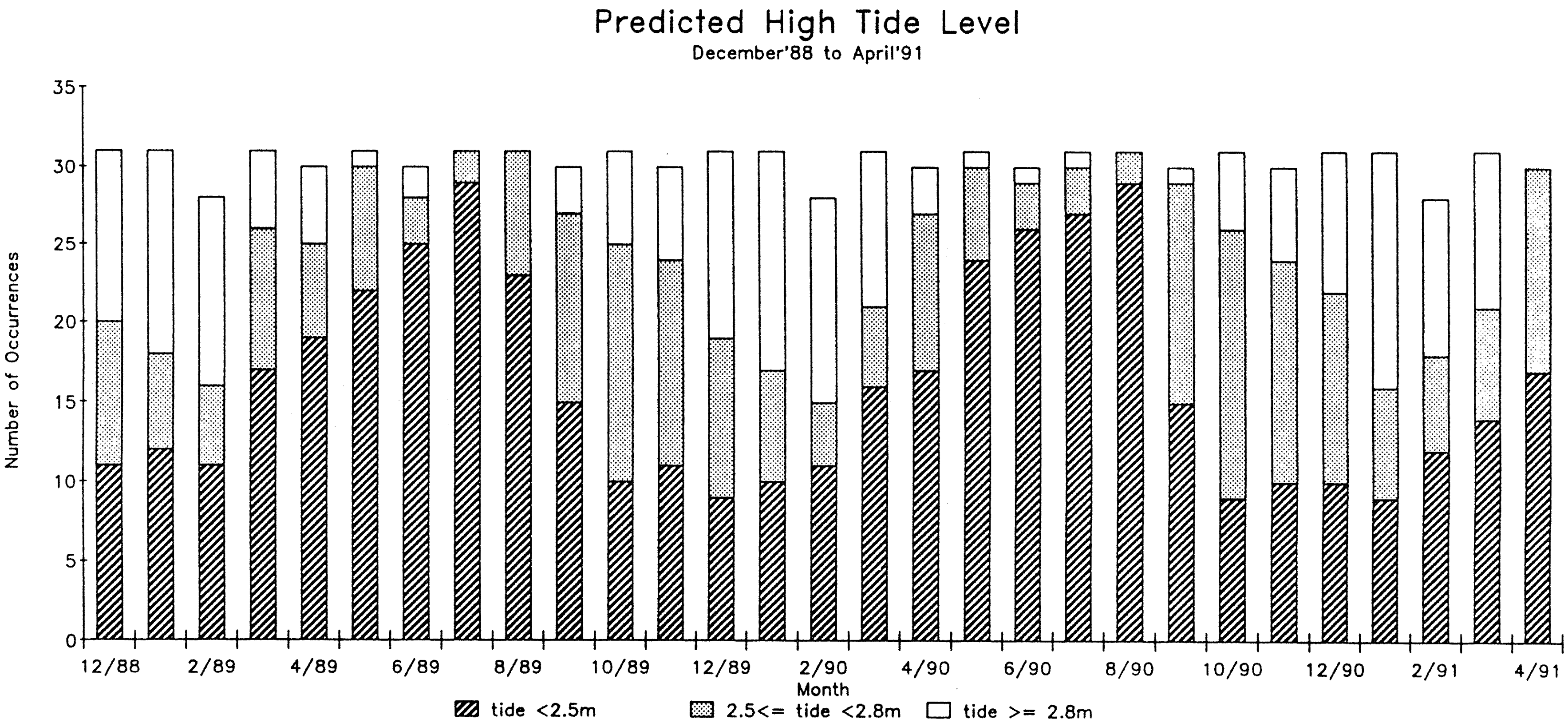


Figure 22. Monthly high tide level occurrences - December 1988 to April 1990

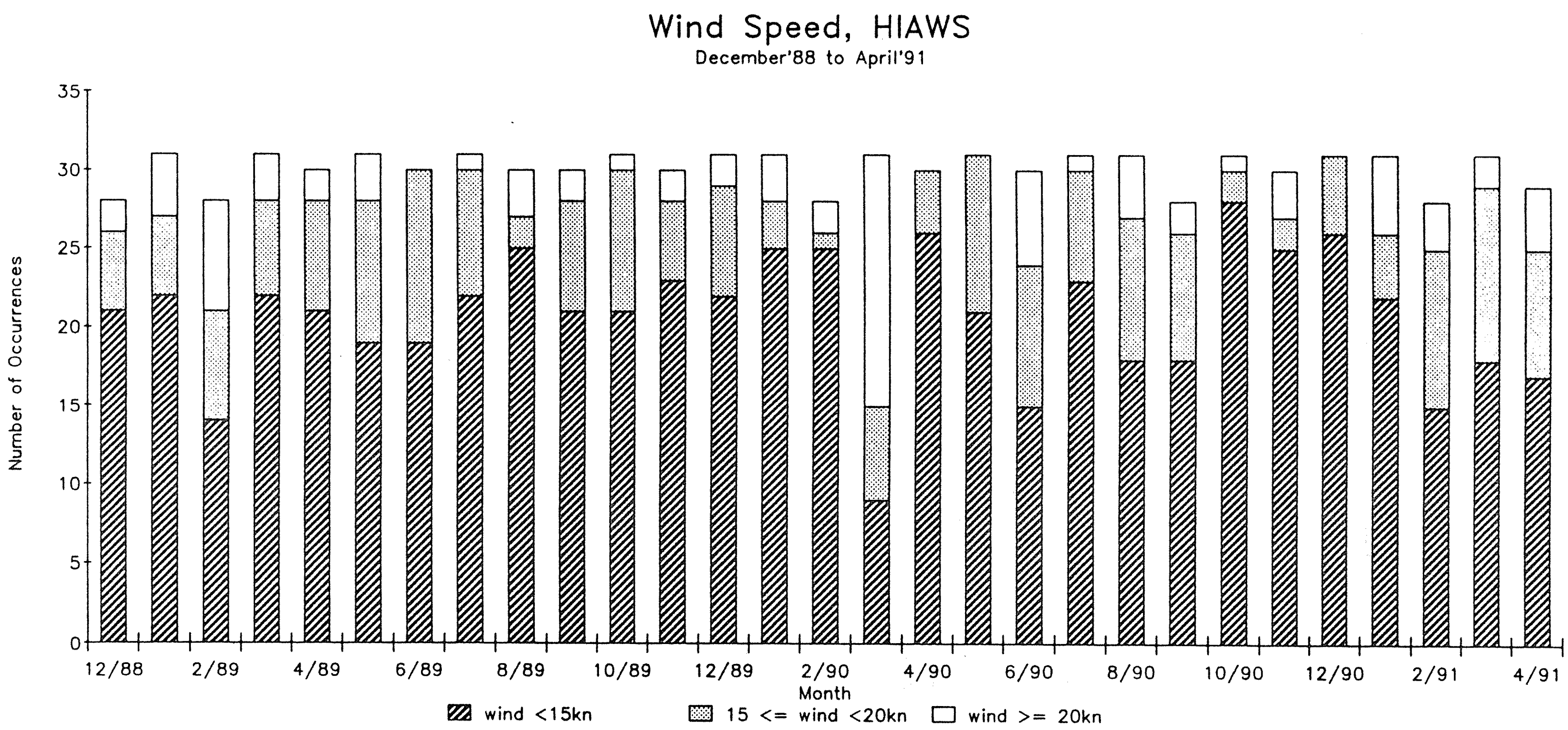


Figure 23. Monthly wind speed occurrences - December 1988 to April 1990

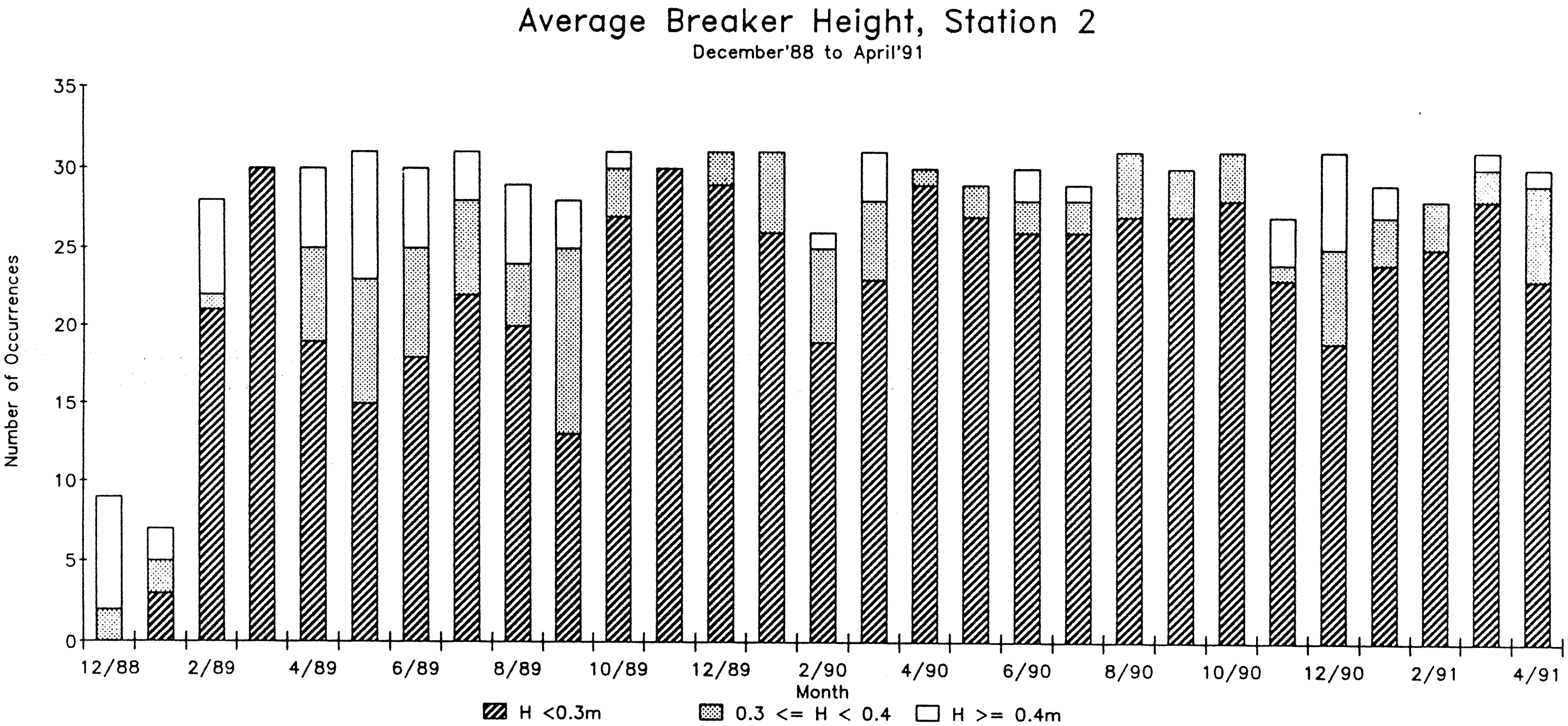


Figure 24. Monthly average breaker height occurrences at station 2 - December 1988 to April 1990

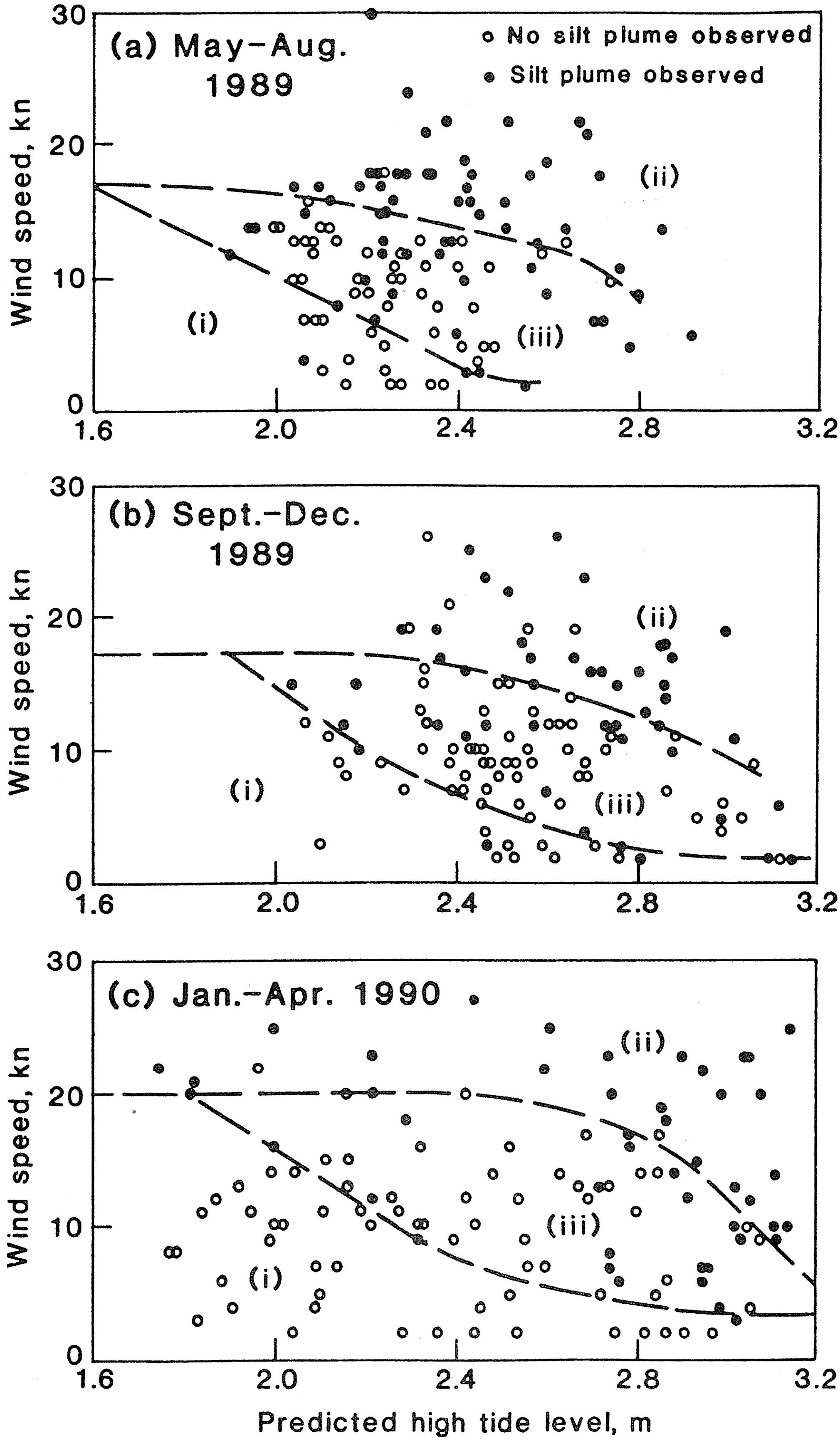


Figure 25. Silt plume occurrences at station 2 for various wind speeds and high tide levels

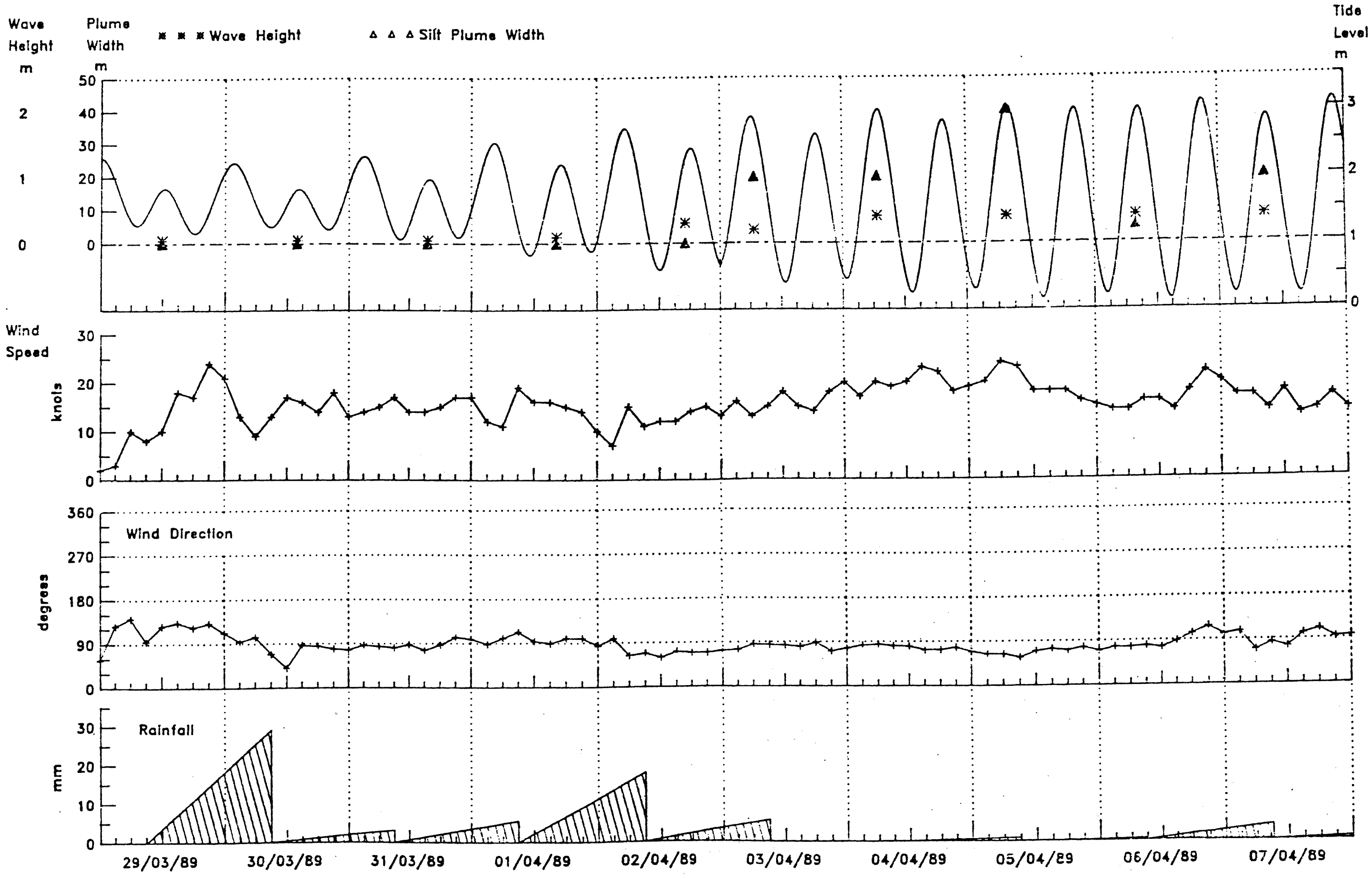


Figure 26. Reef top waves and tidal conditions

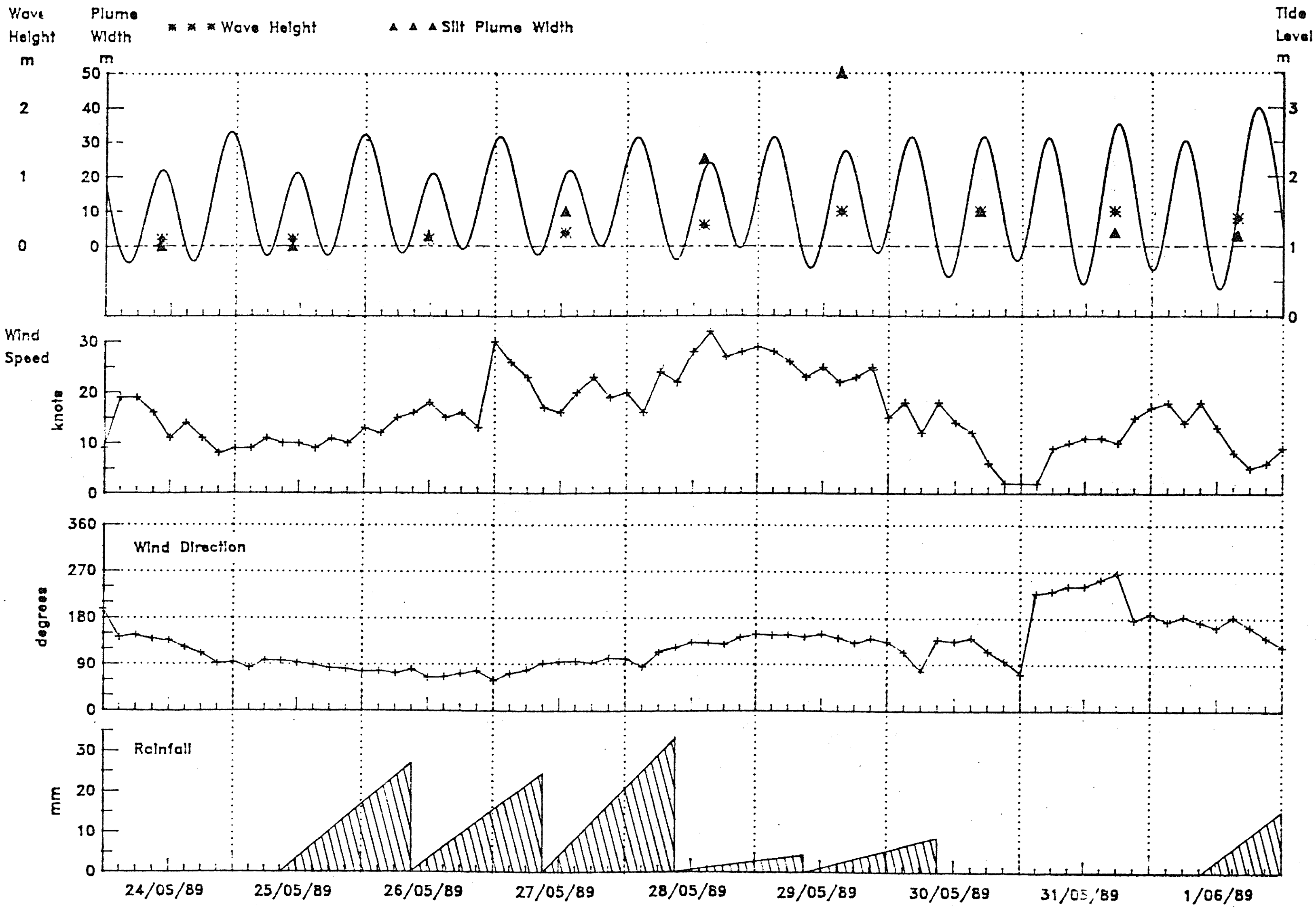


Figure 27. Meteorological event EO - 29 March to 7 April 1989

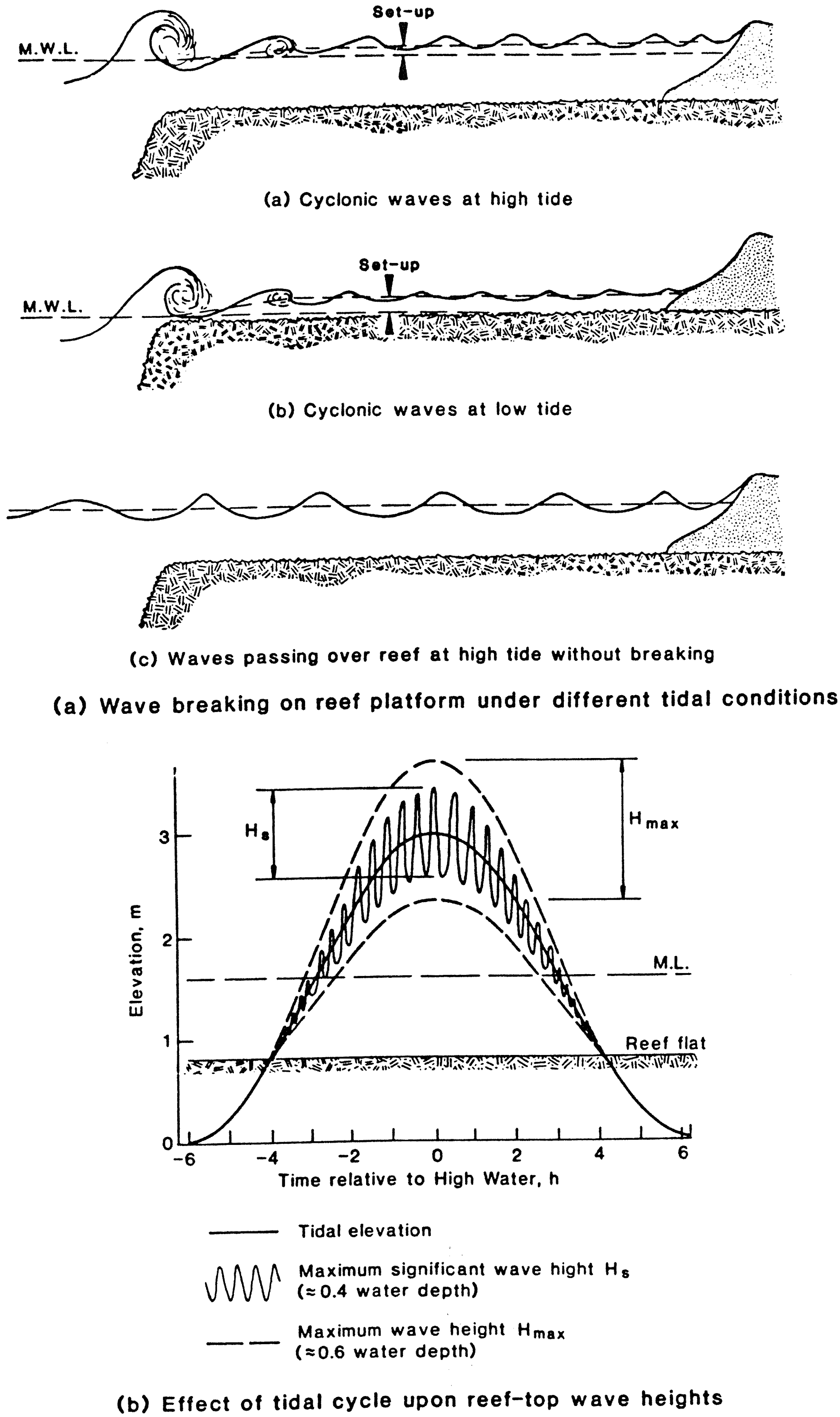


Figure 28. Meteorological event E1 - 25 May to 1 June 1989

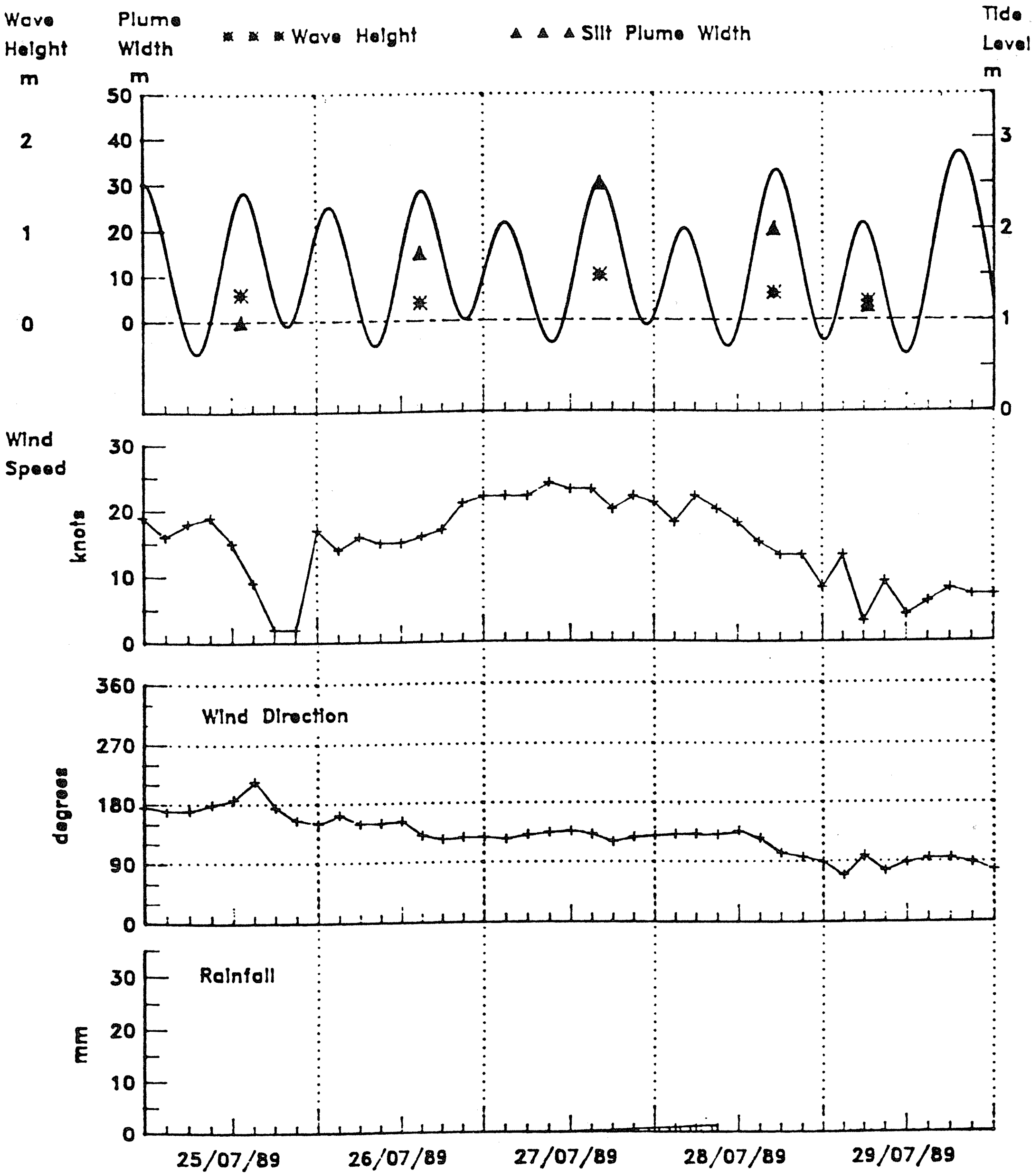


Figure 29. Meteorological event E2 - 25 to 29 July 1989

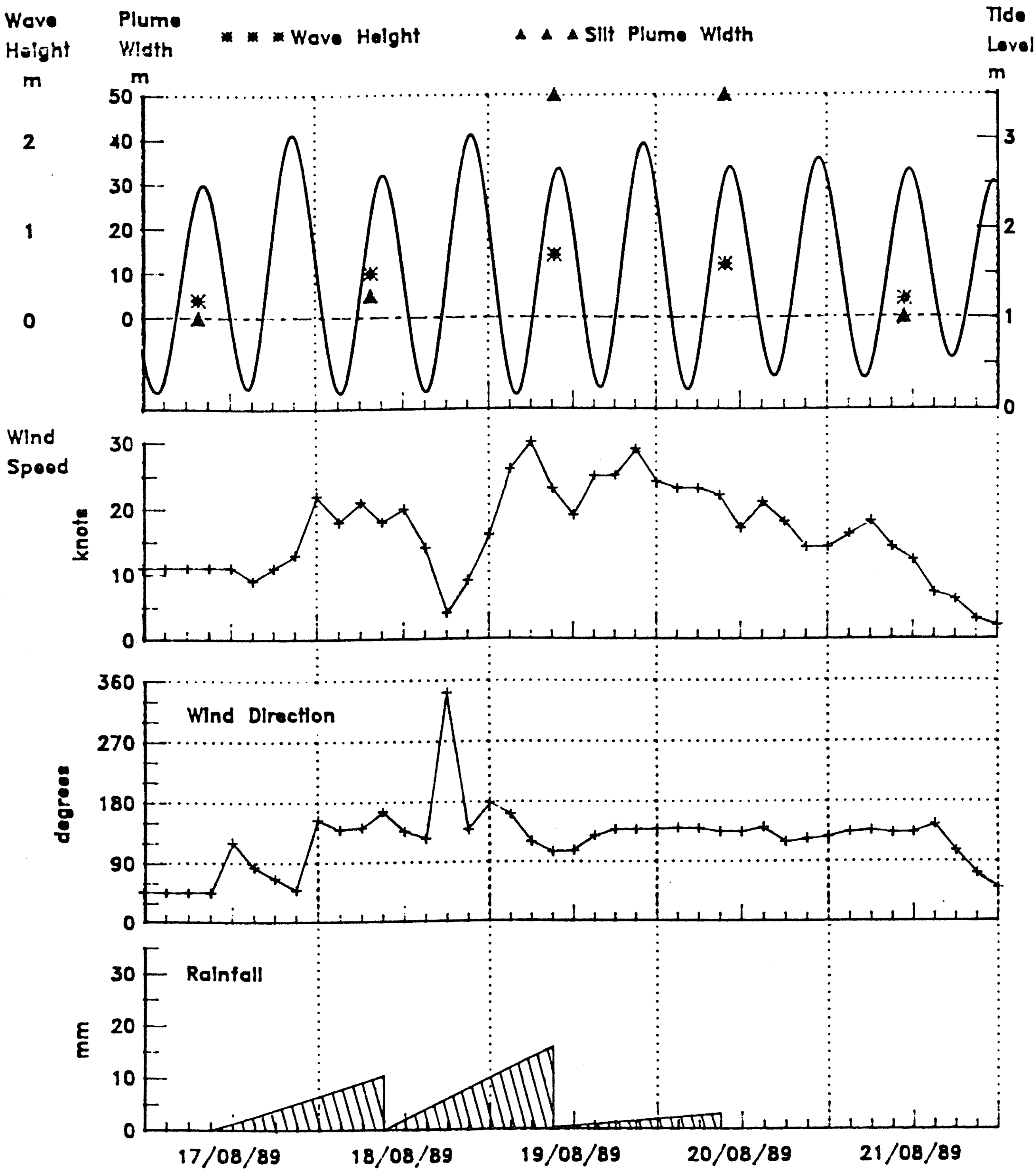


Figure 30. Meteorological event E3 - 17 to 21 August 1989

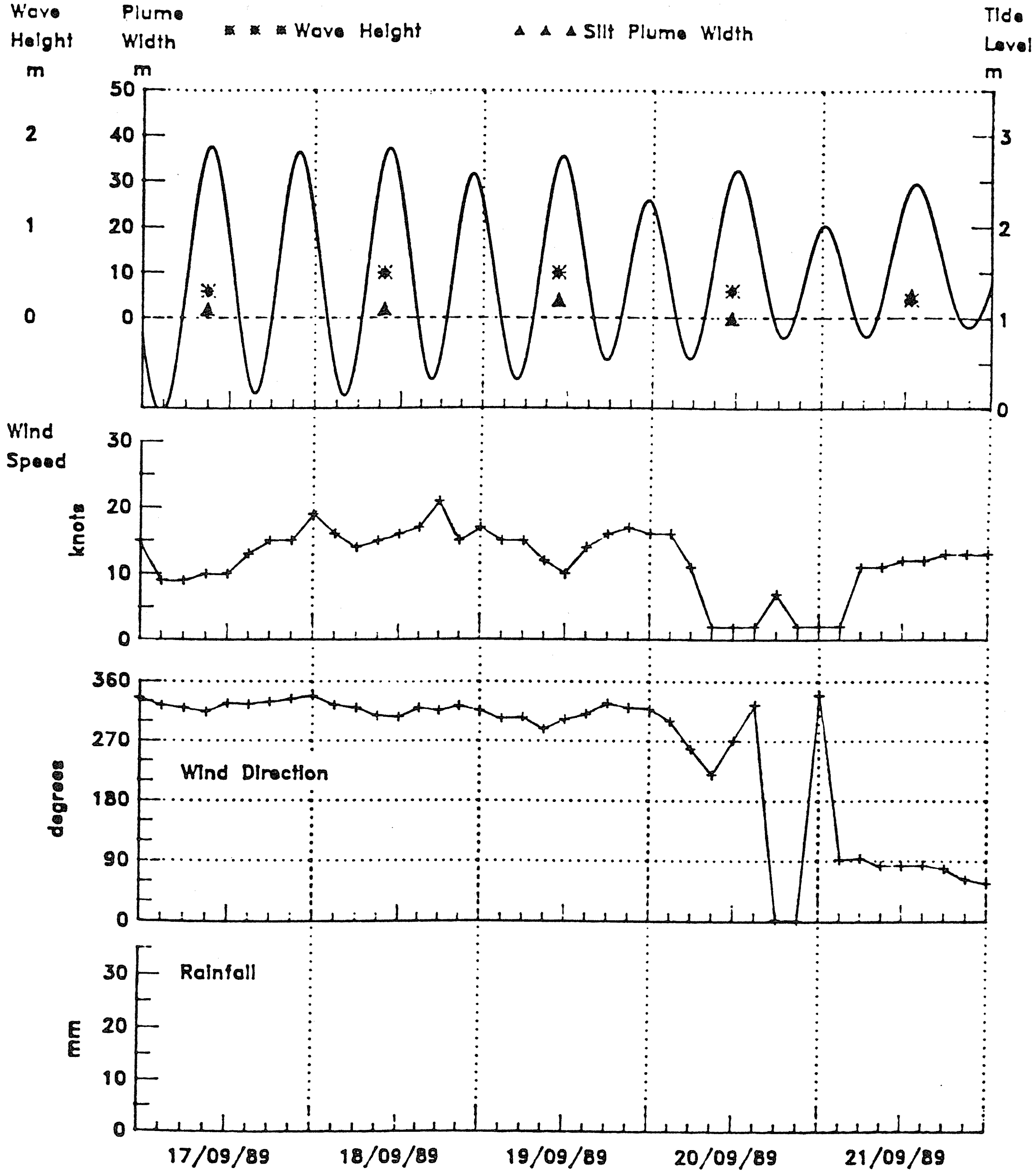


Figure 31. Meteorological event E4 - 17 to 21 September 1989

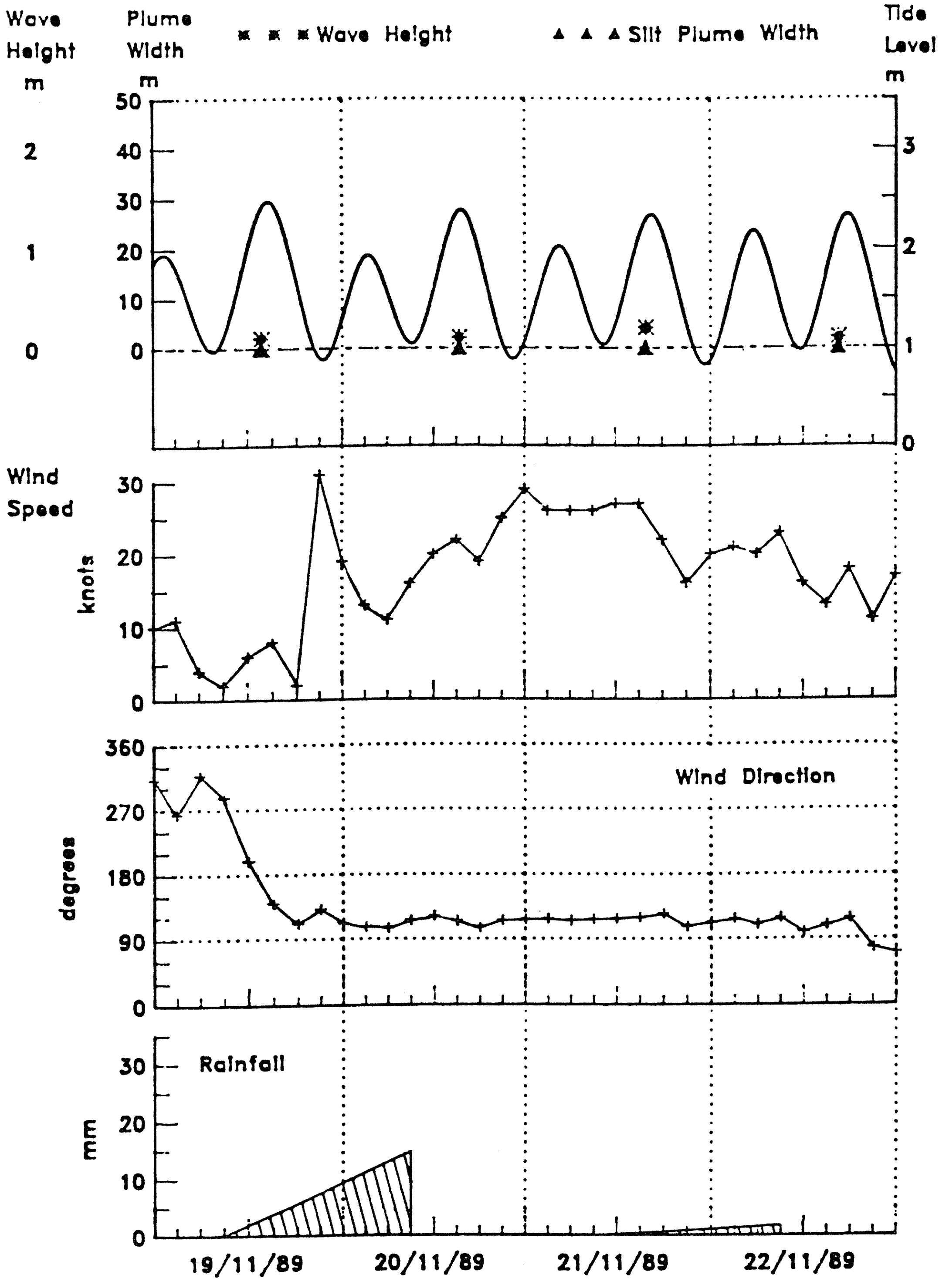


Figure 32. Meteorological event E5 - 19 to 22 November 1989

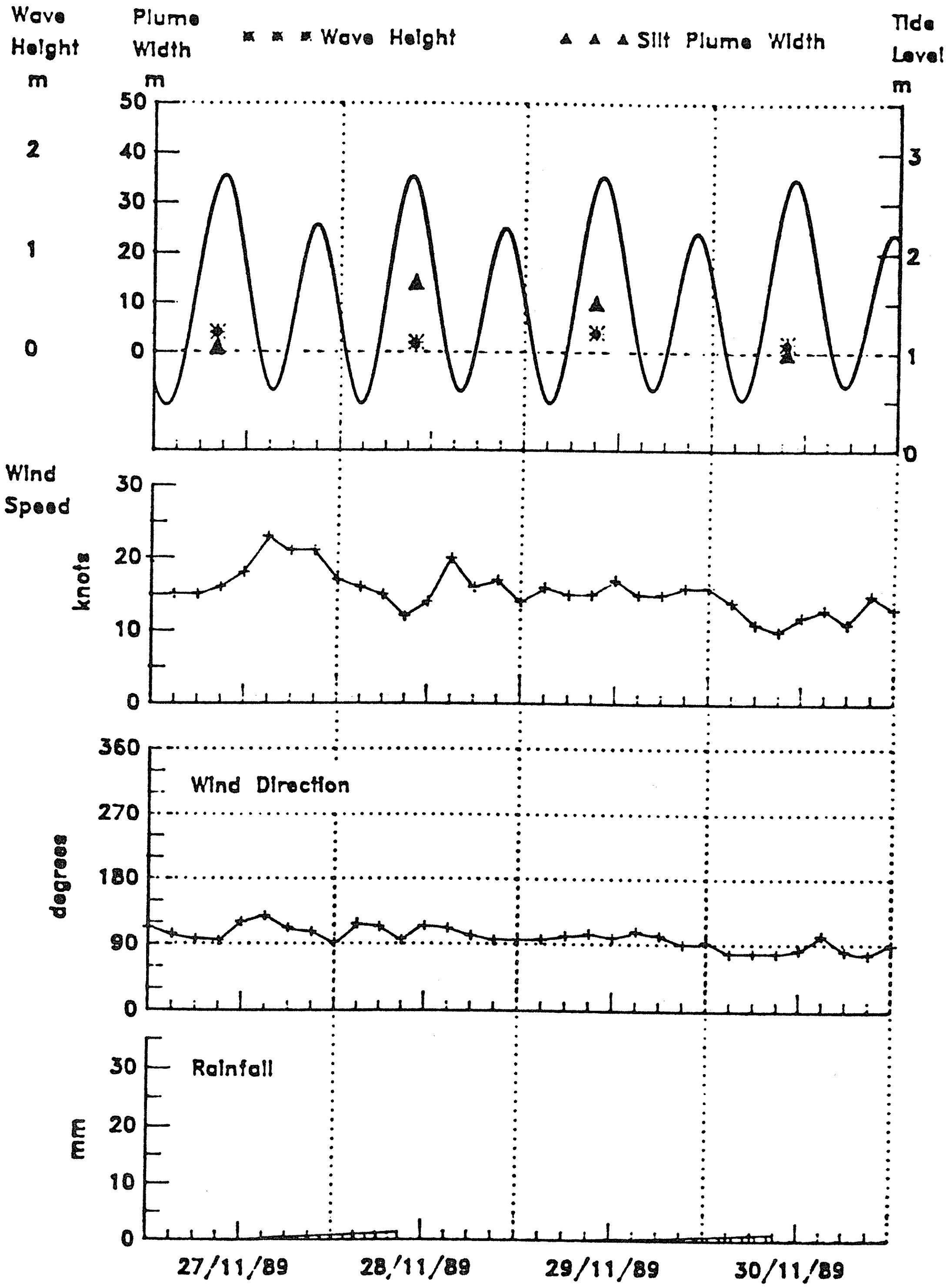


Figure 33. Meteorological event E6 - 27 to 30 November 1989

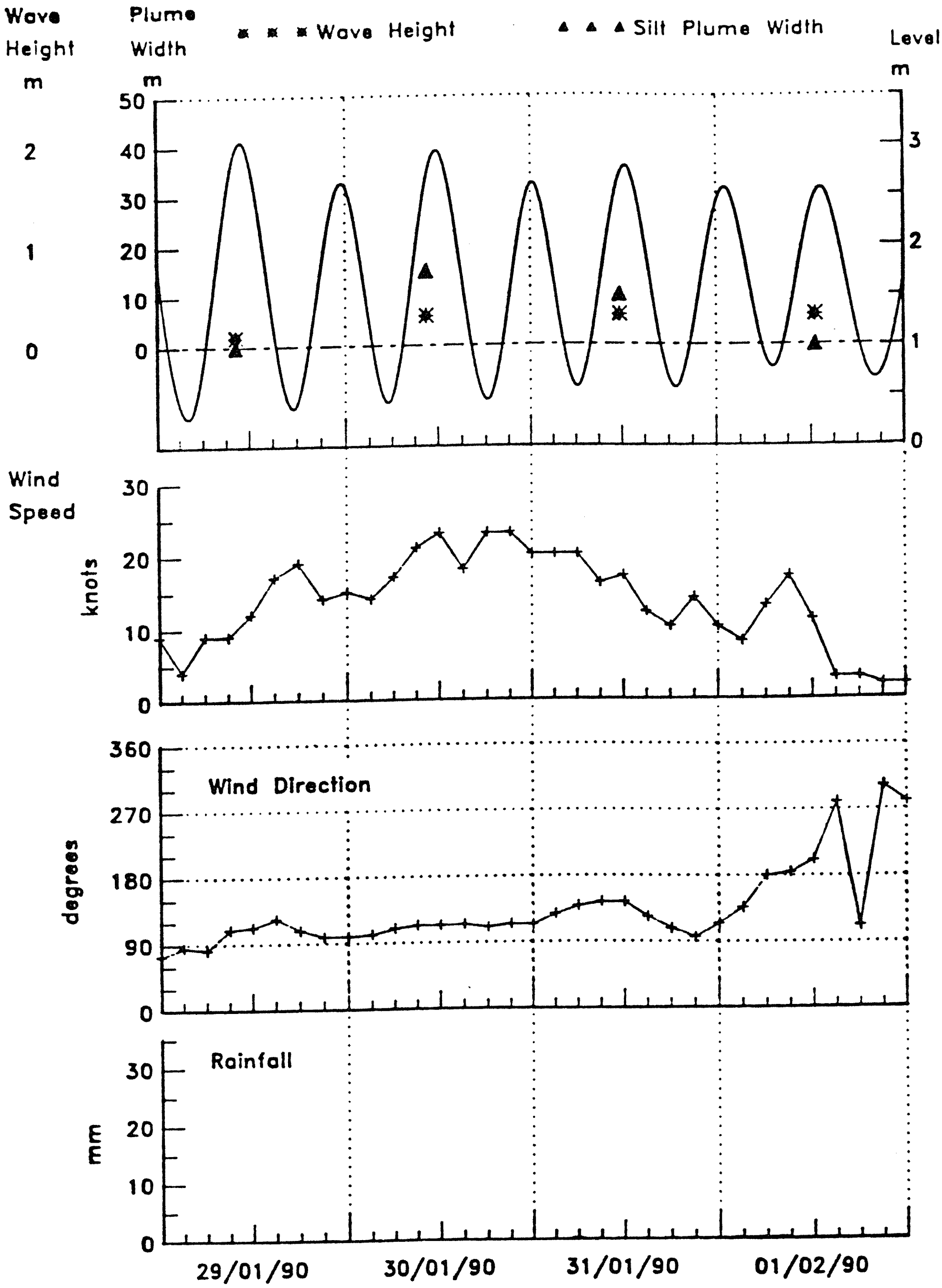


Figure 34. Meteorological event E7 - 29 January to 2 February 1990

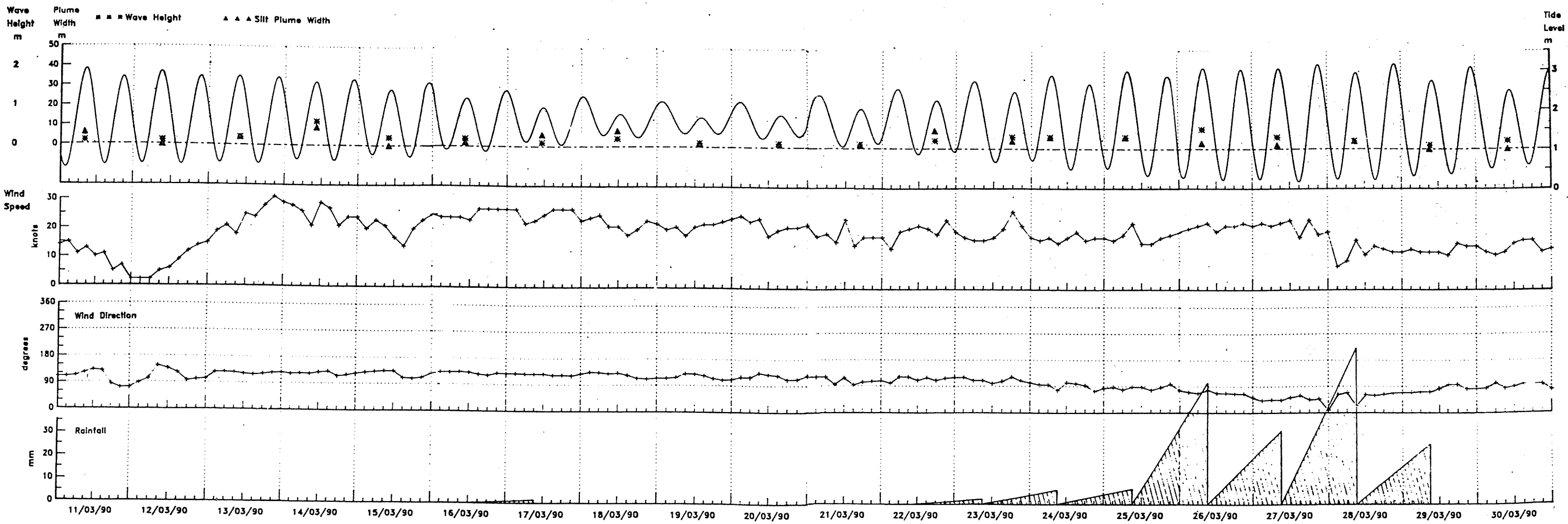


Figure 35. Meteorological event E8 - 11 to 30 March 1990

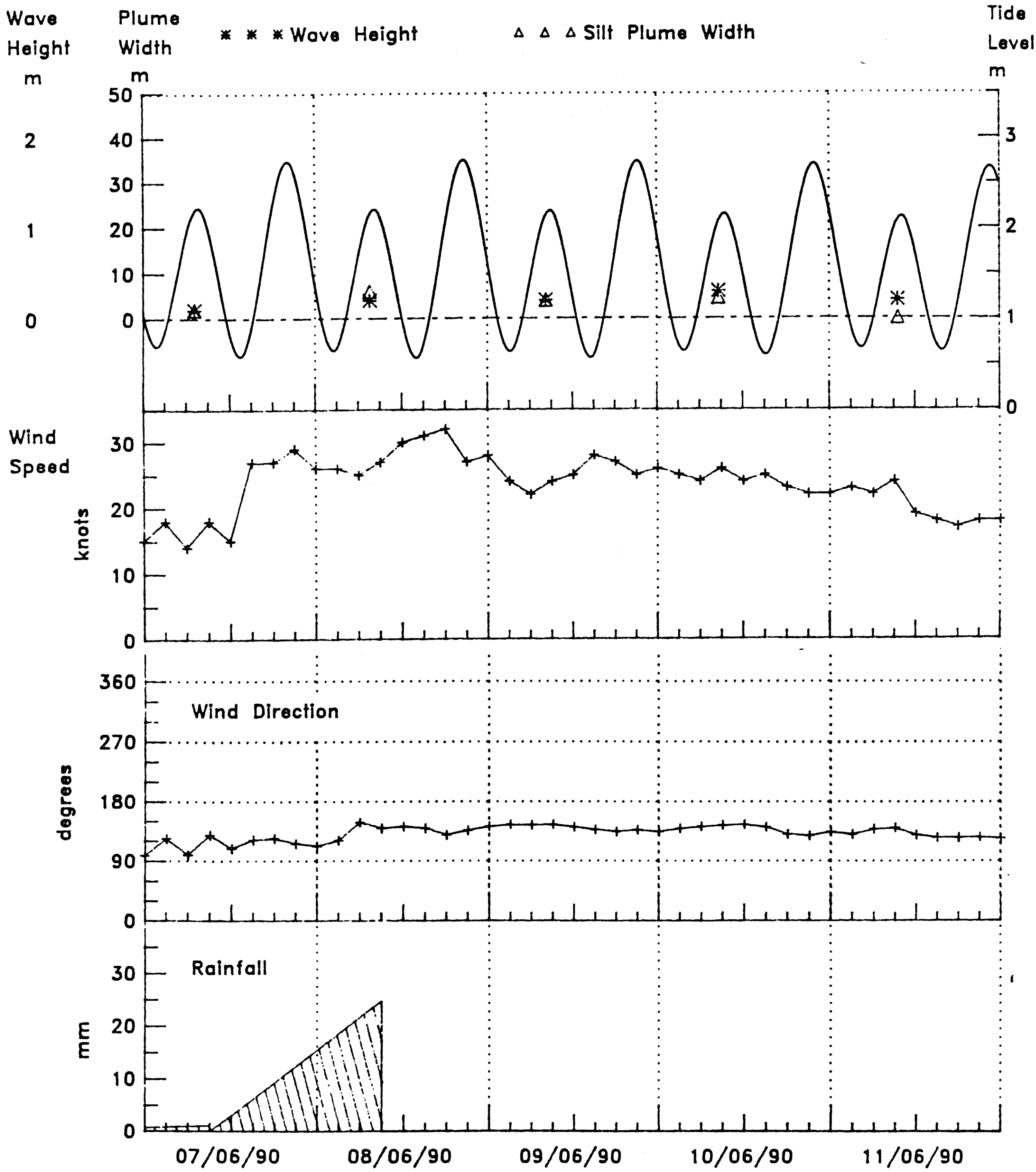


Figure 36. Meteorological event E9 - 7 to 11 June 1990

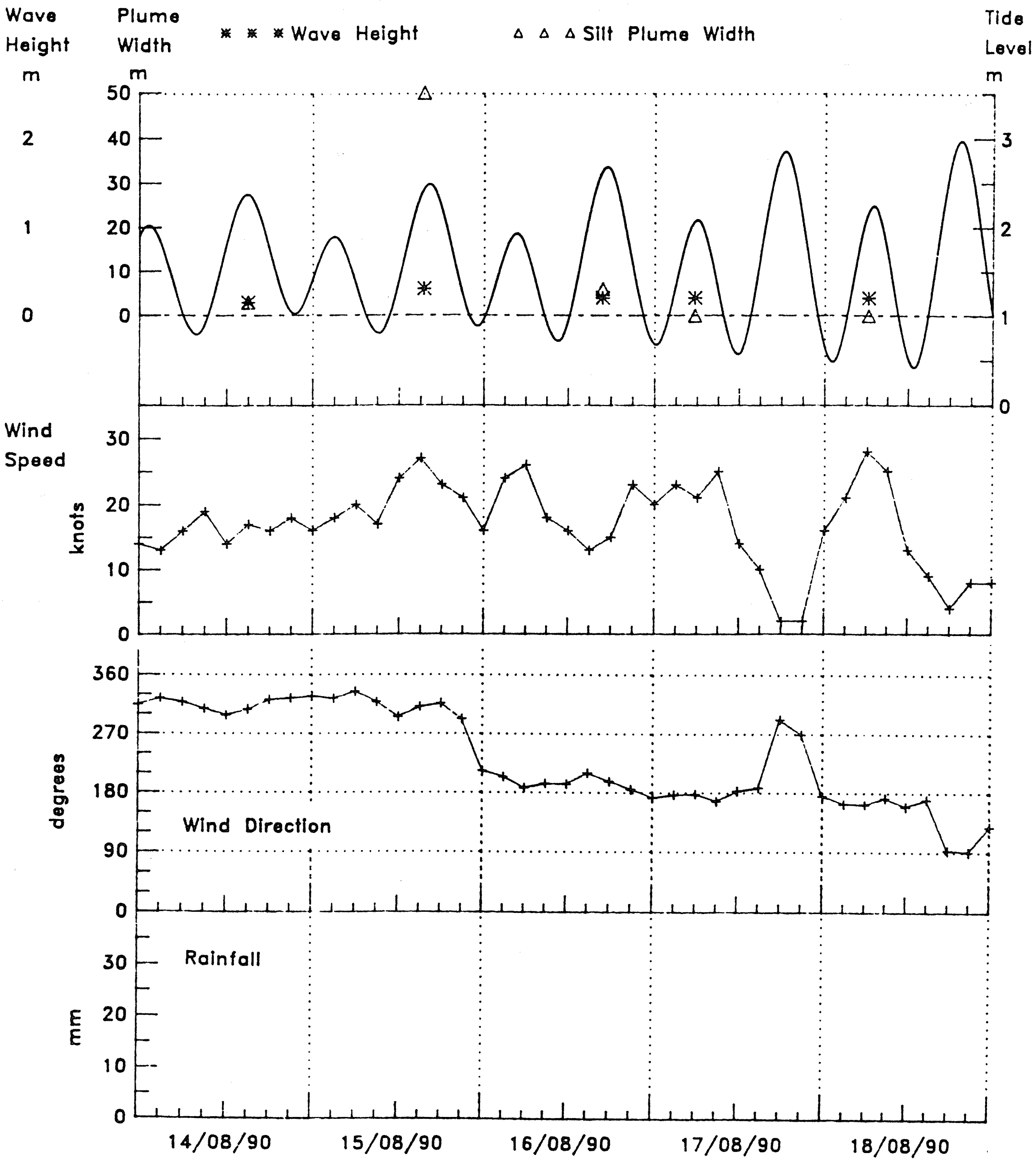


Figure 37. Meteorological event E10 - 14 to 18 August 1990

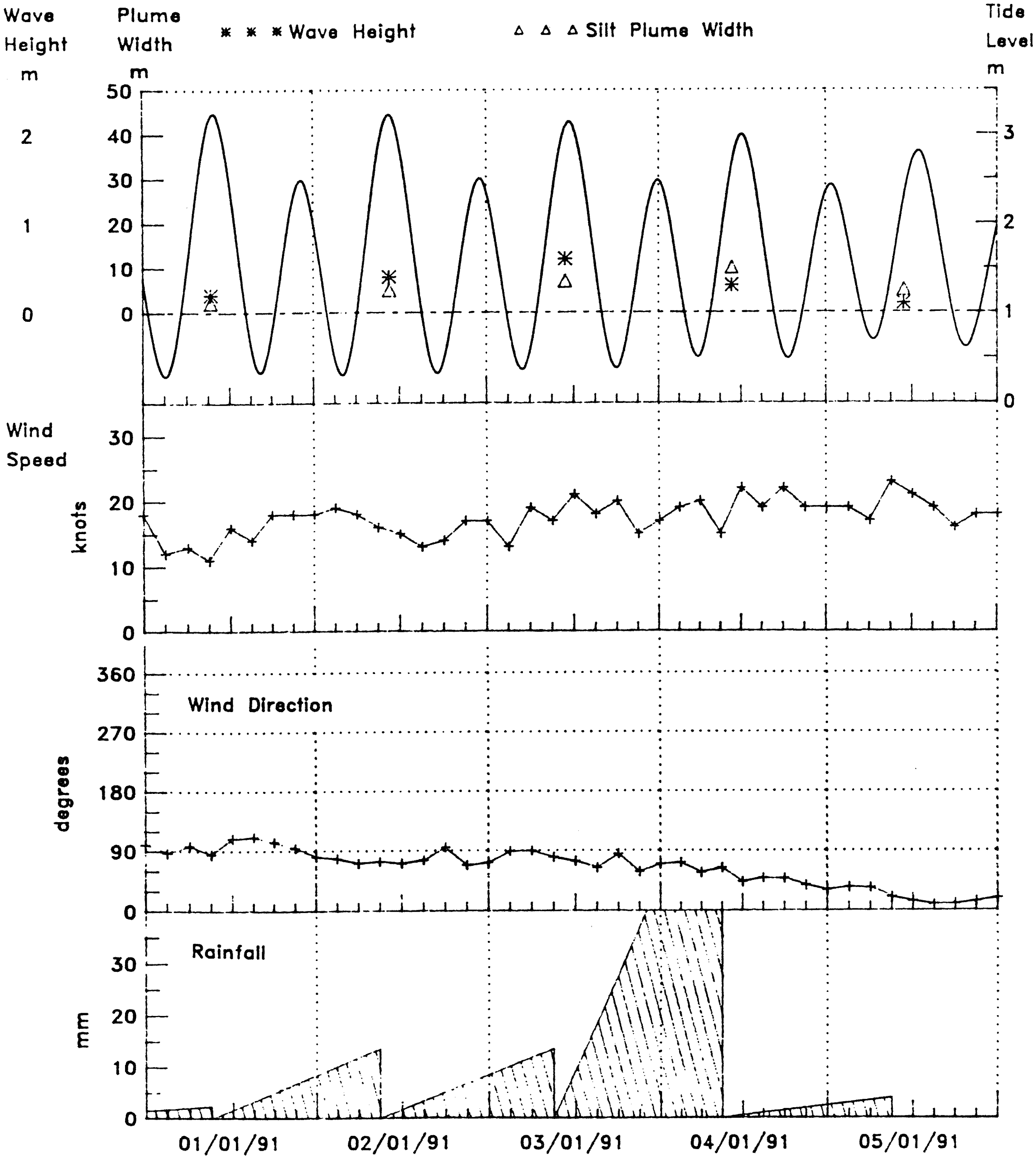


Figure 38. Meteorological event E11 - 1 to 5 January 1991

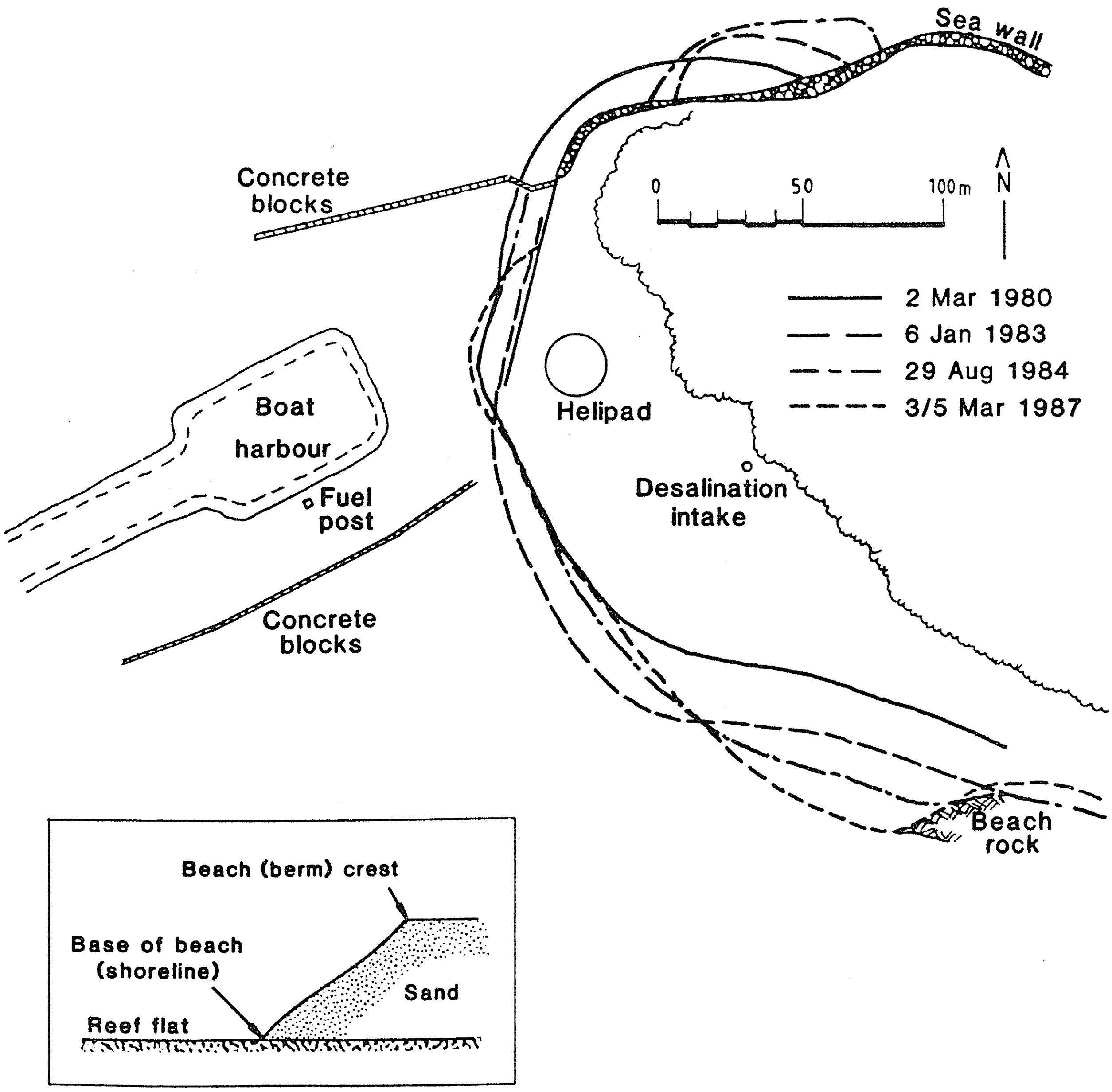


Figure 39. Shoreline changes - 1980 to 1987

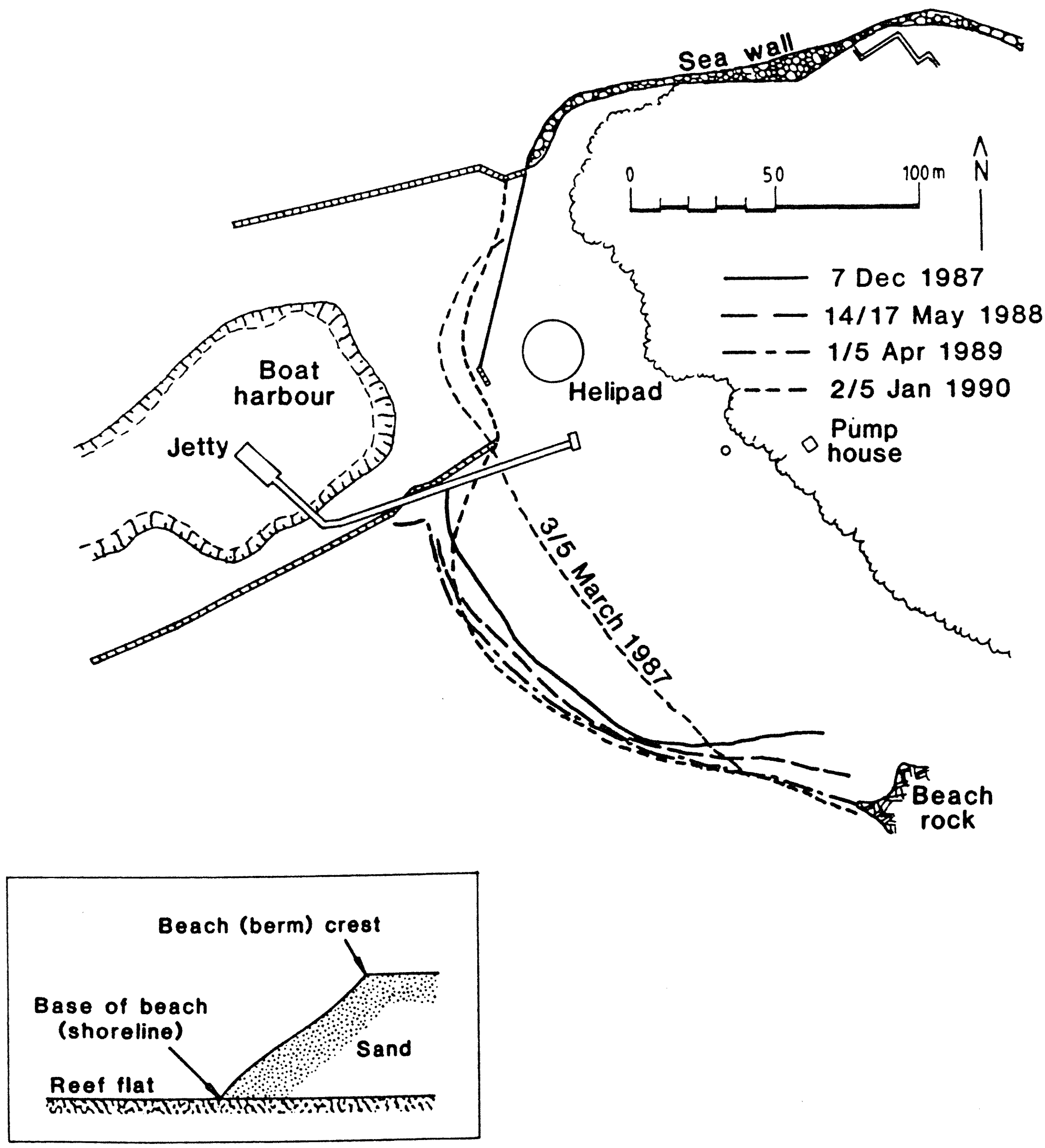
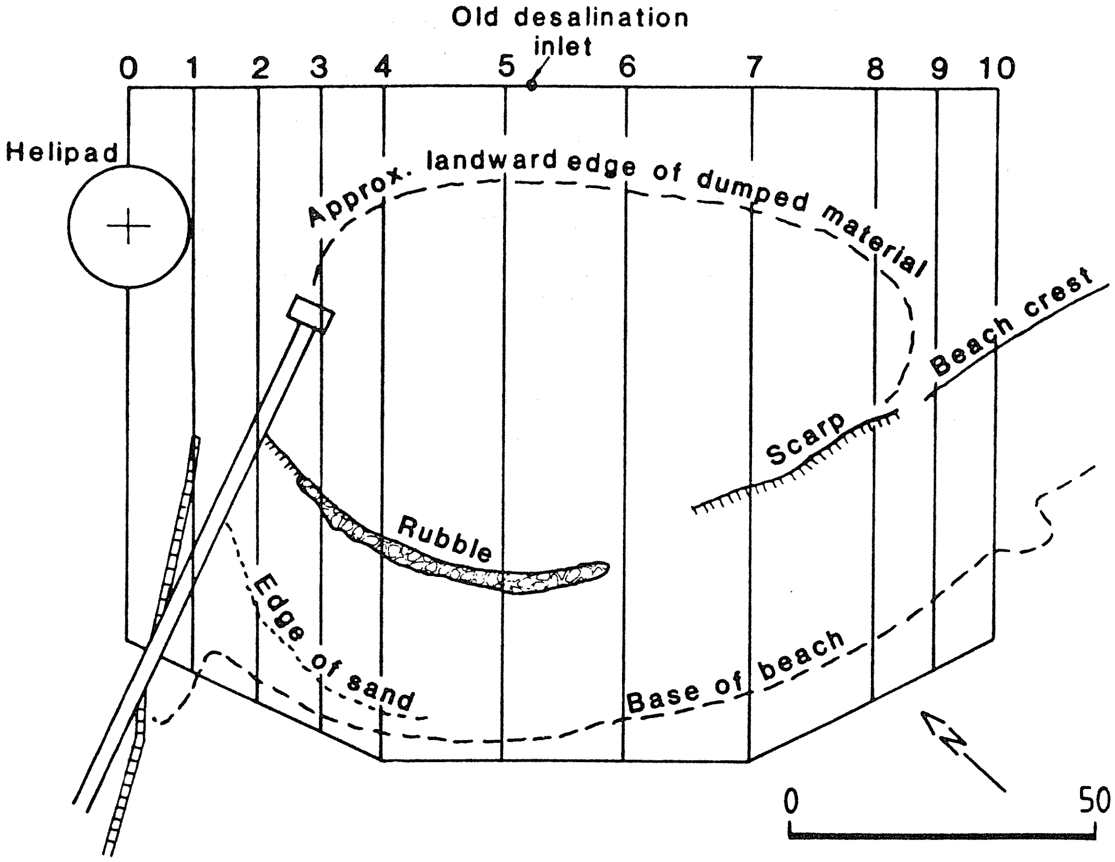
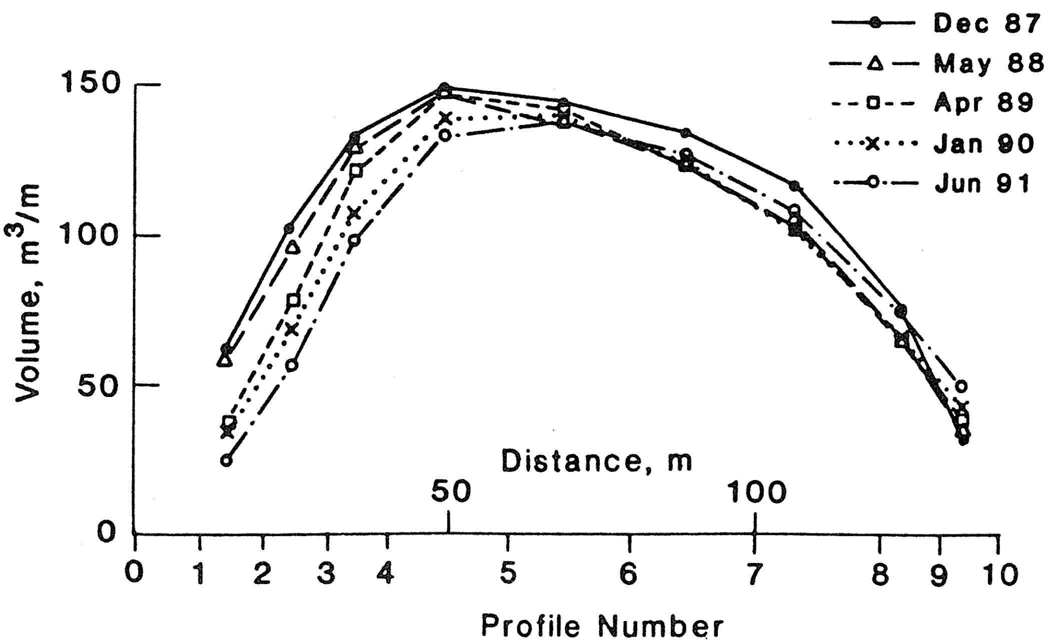


Figure 40. Shoreline changes - 1987 to 1990



Location of profiles used for volume calculations



Volume changes along spoil dump relative to August 1984

Figure 41. Volume changes along spoil dump relative to August 1984

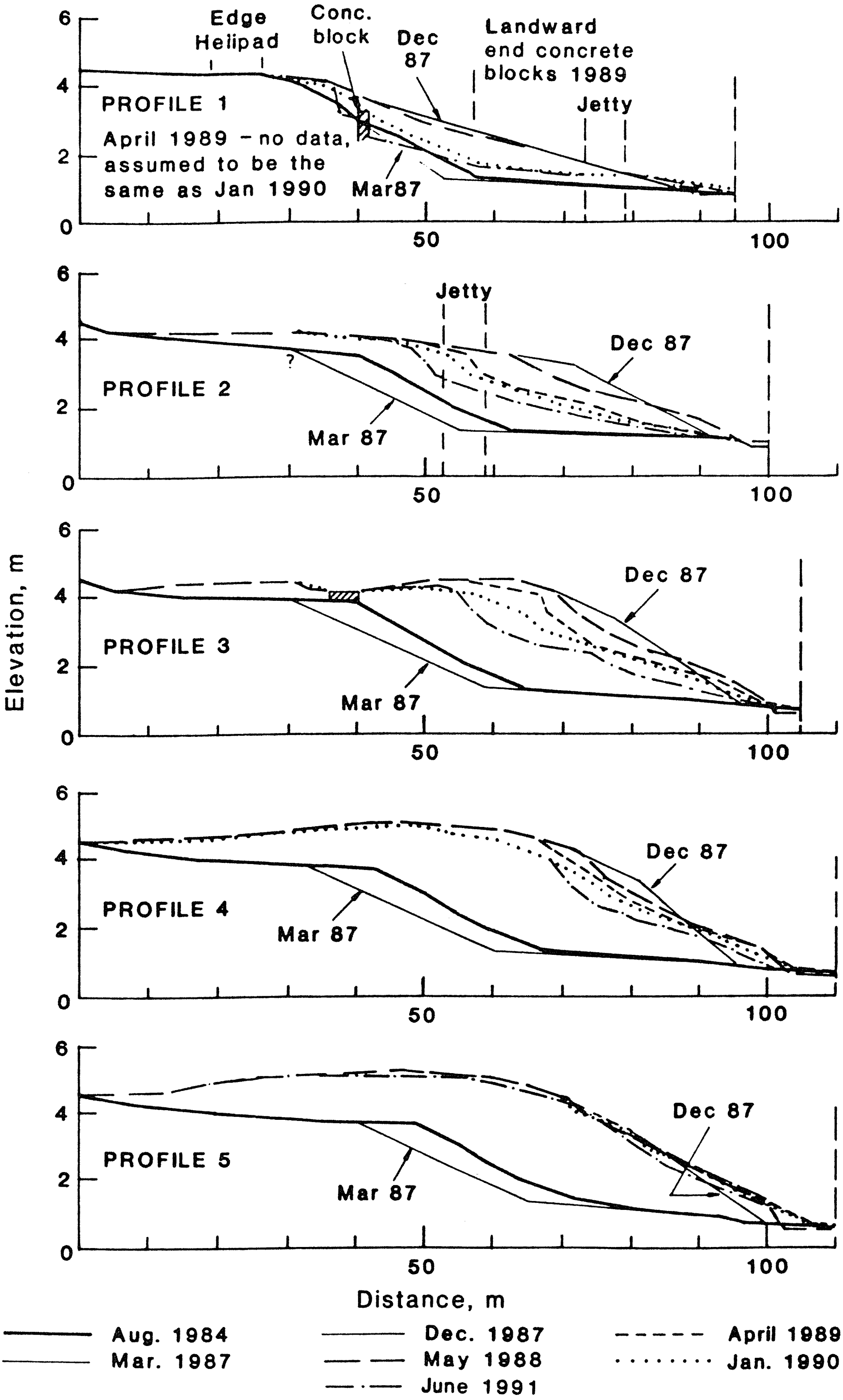


Figure 42. Spoil dump Profiles 1 to 5

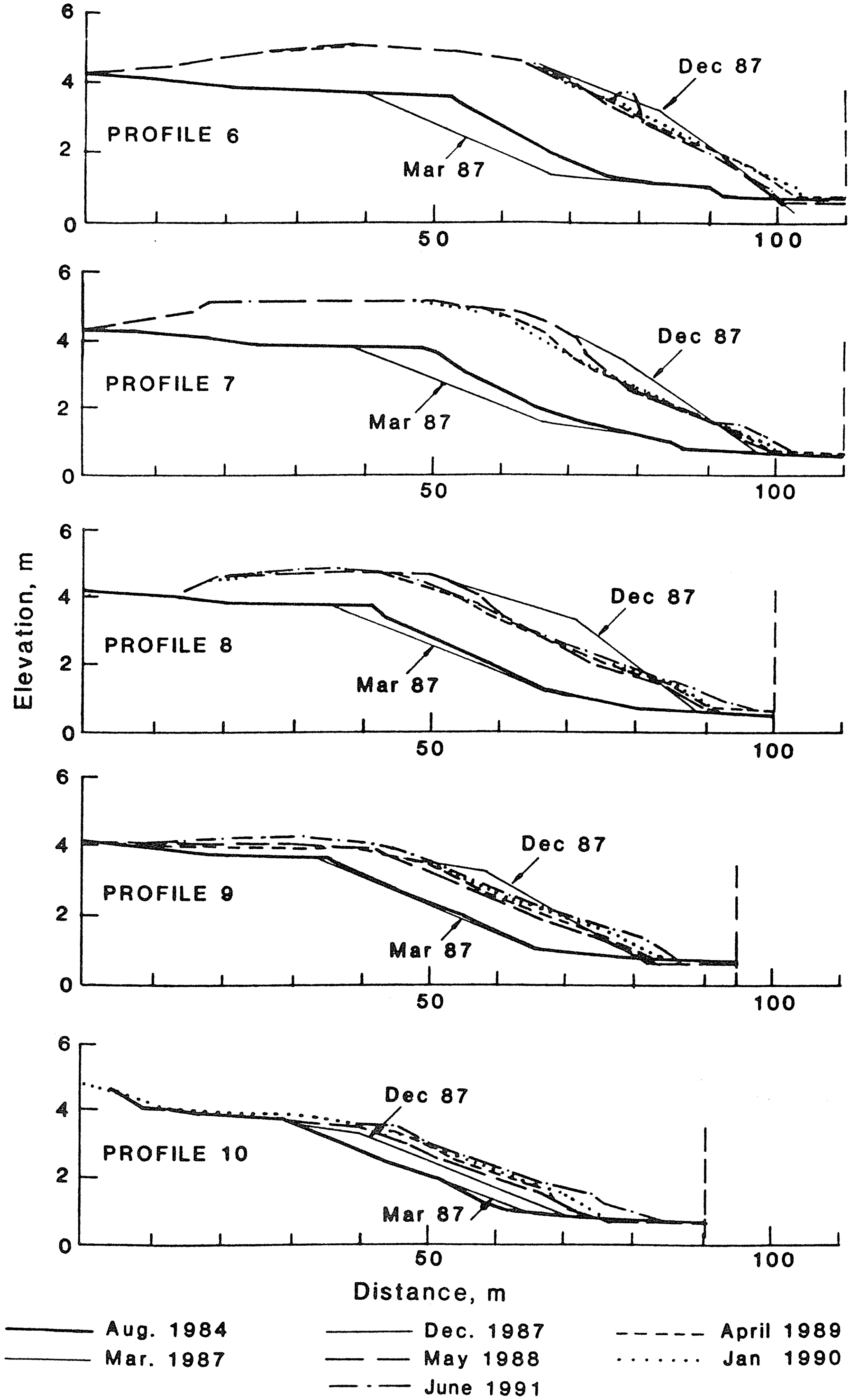


Figure 43. Spoil dump Profiles 6 to 10

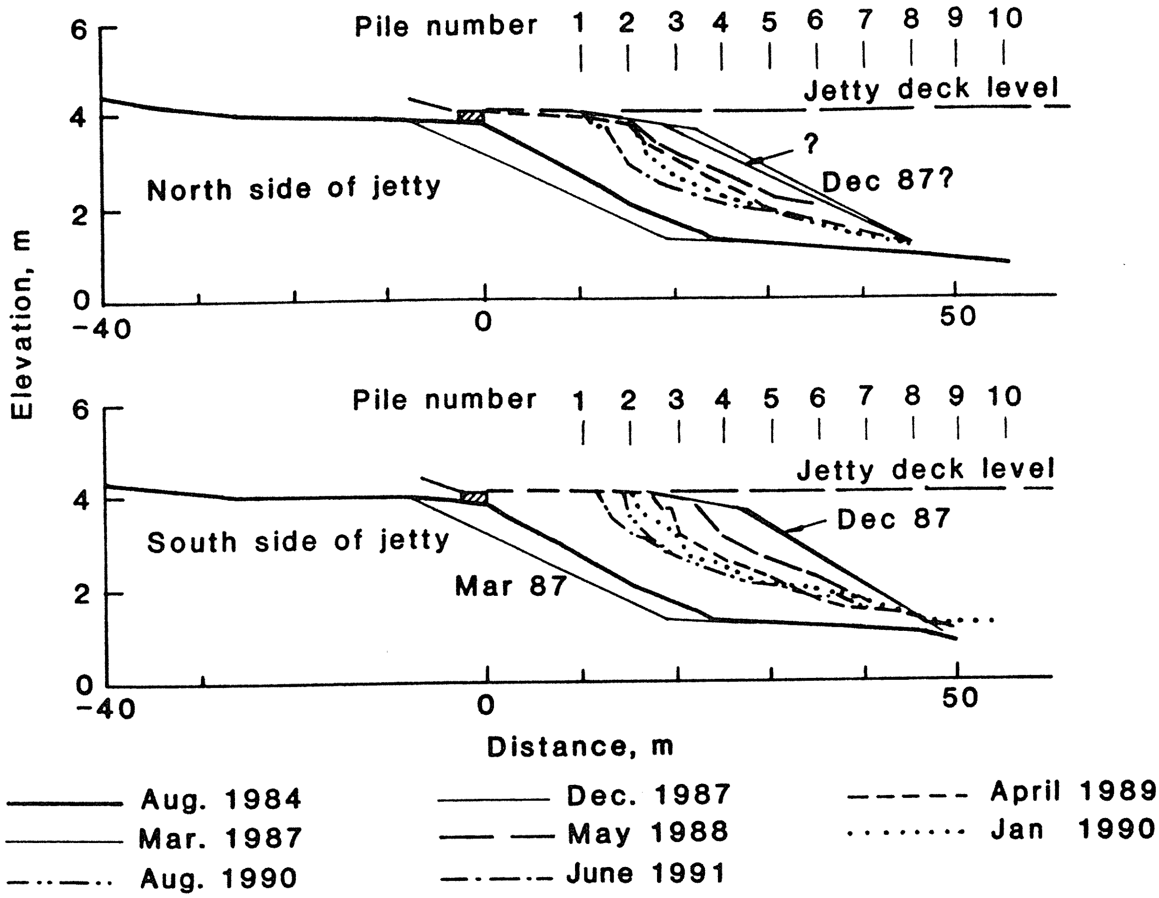


Figure 44. Beach profiles at jetty

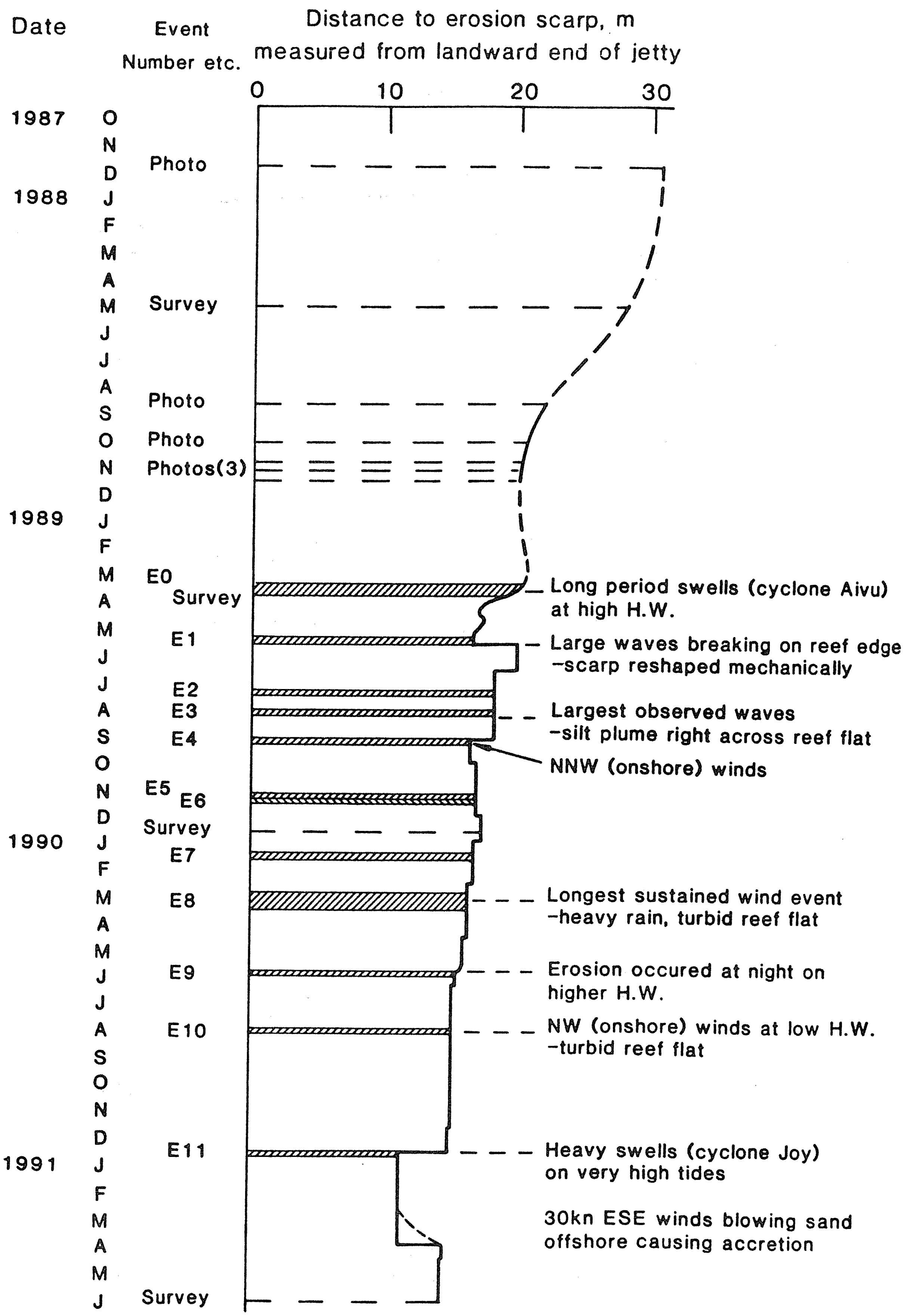
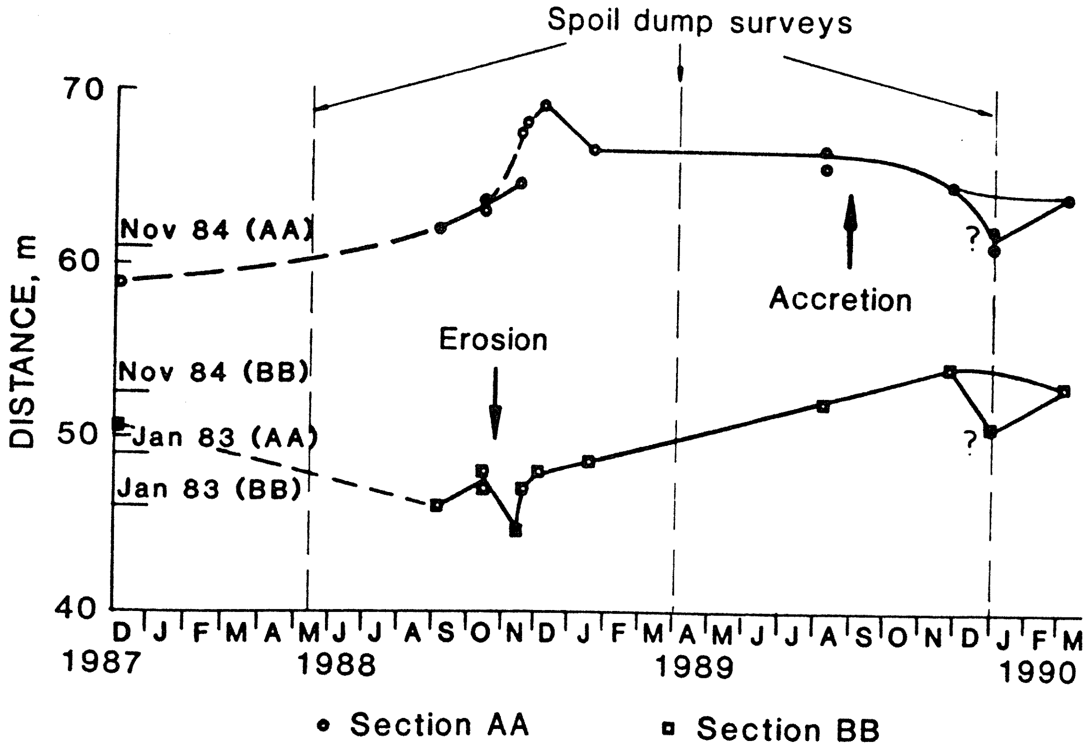


Figure 45. Scarp recession on southern side of jetty



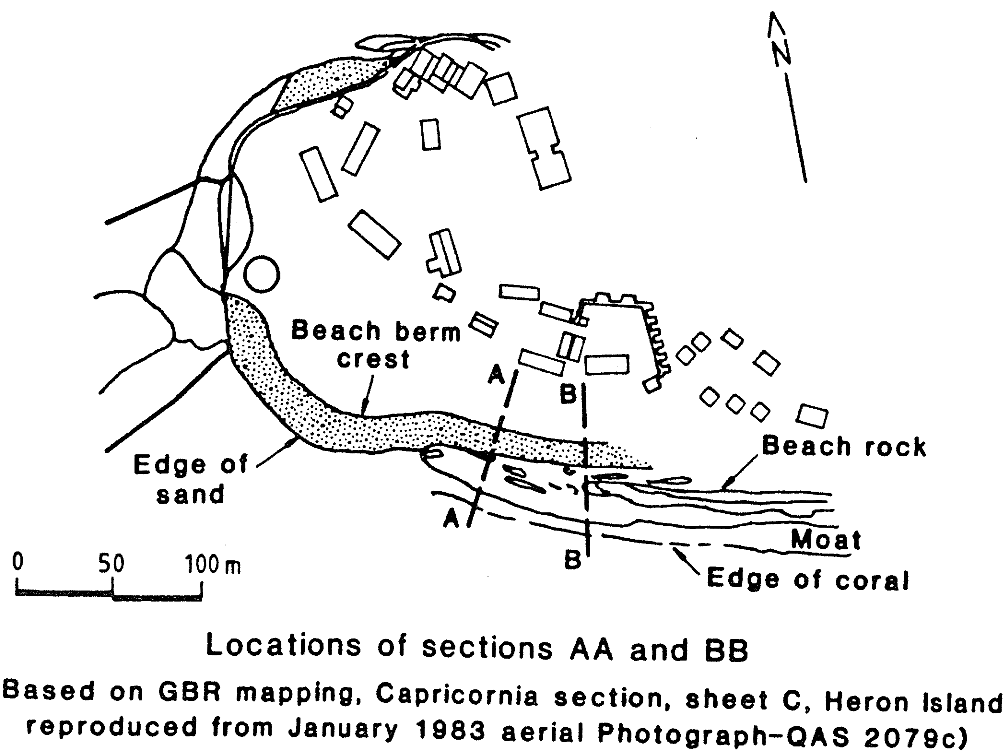


Figure 46. Shoreline changes east of spoil dump

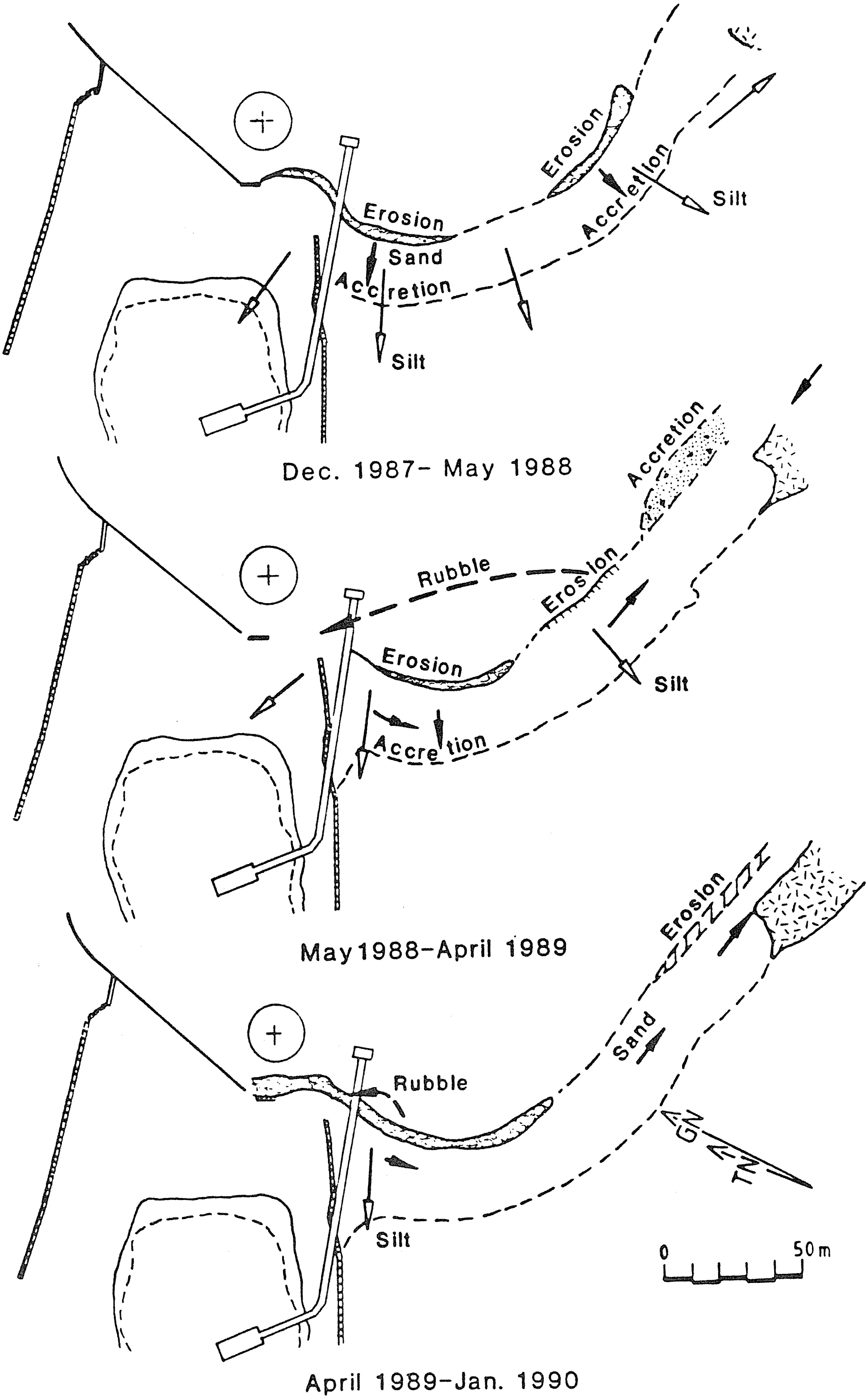


Figure 47. Erosion - accretion pattern at spoil dump

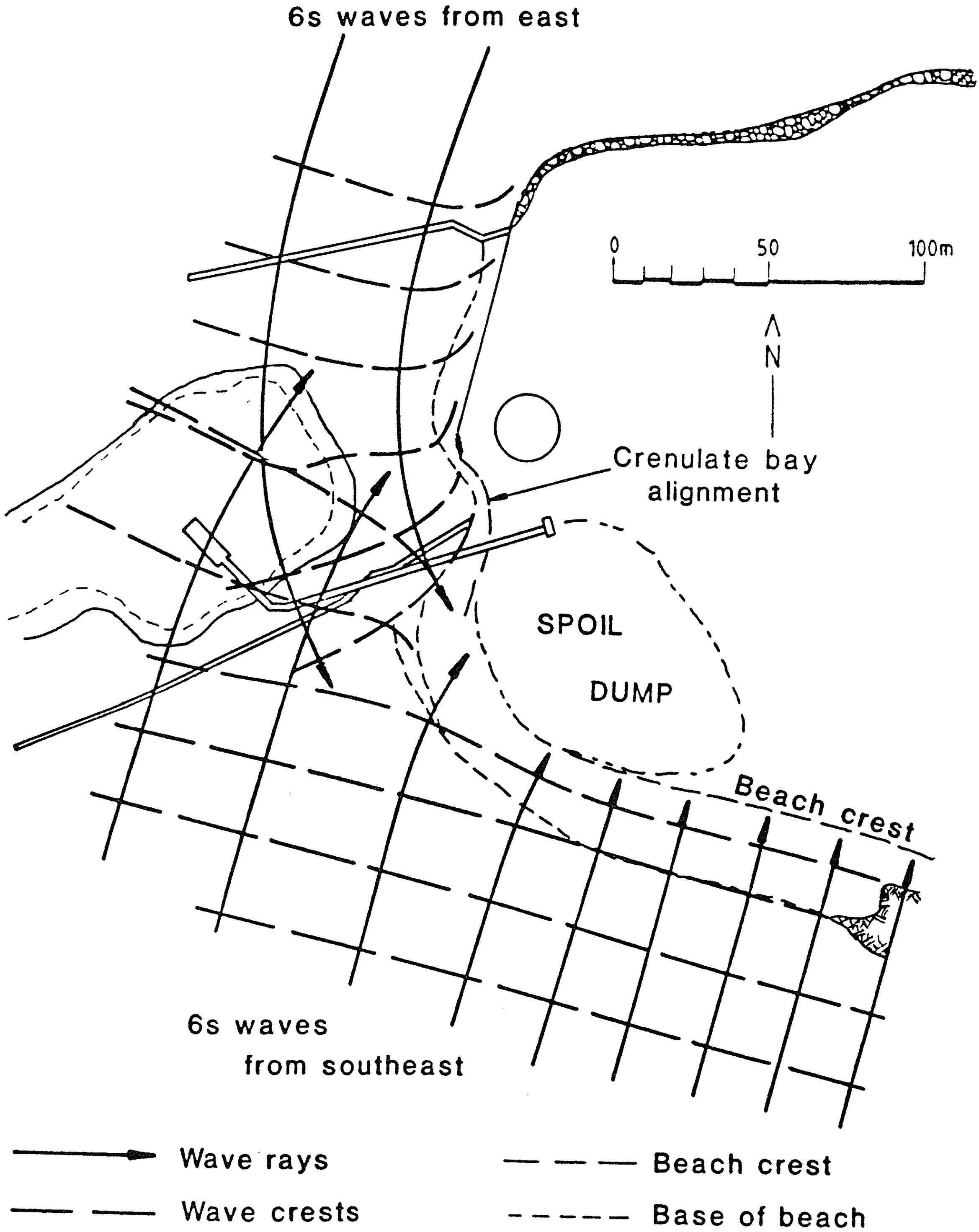


Figure 48. Spoil dump shoreline realignment

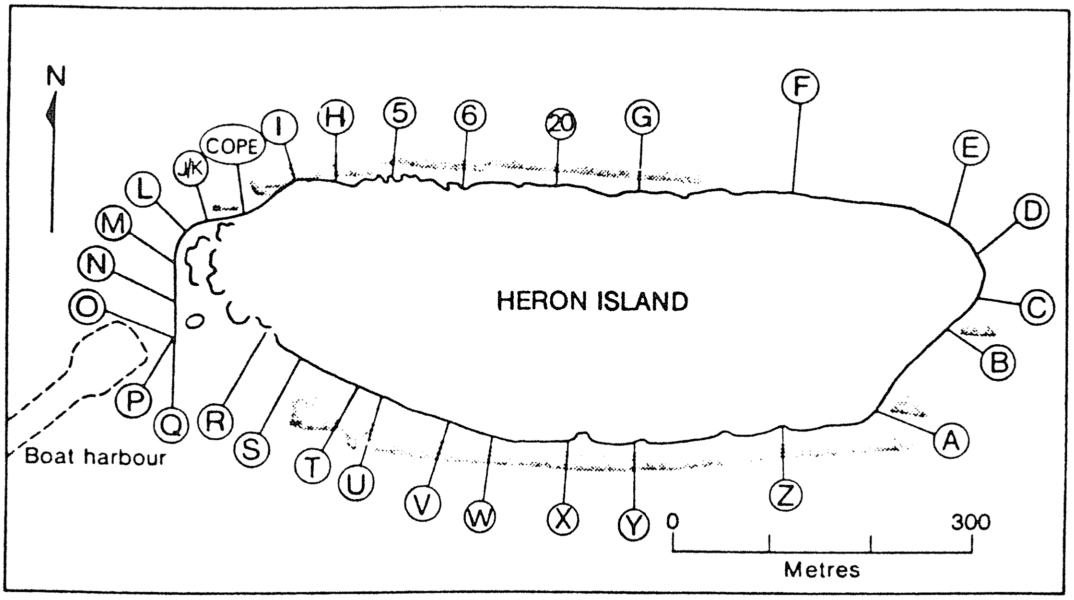


Figure 49. Location of Flood's beach observation stations (Flood 1984)

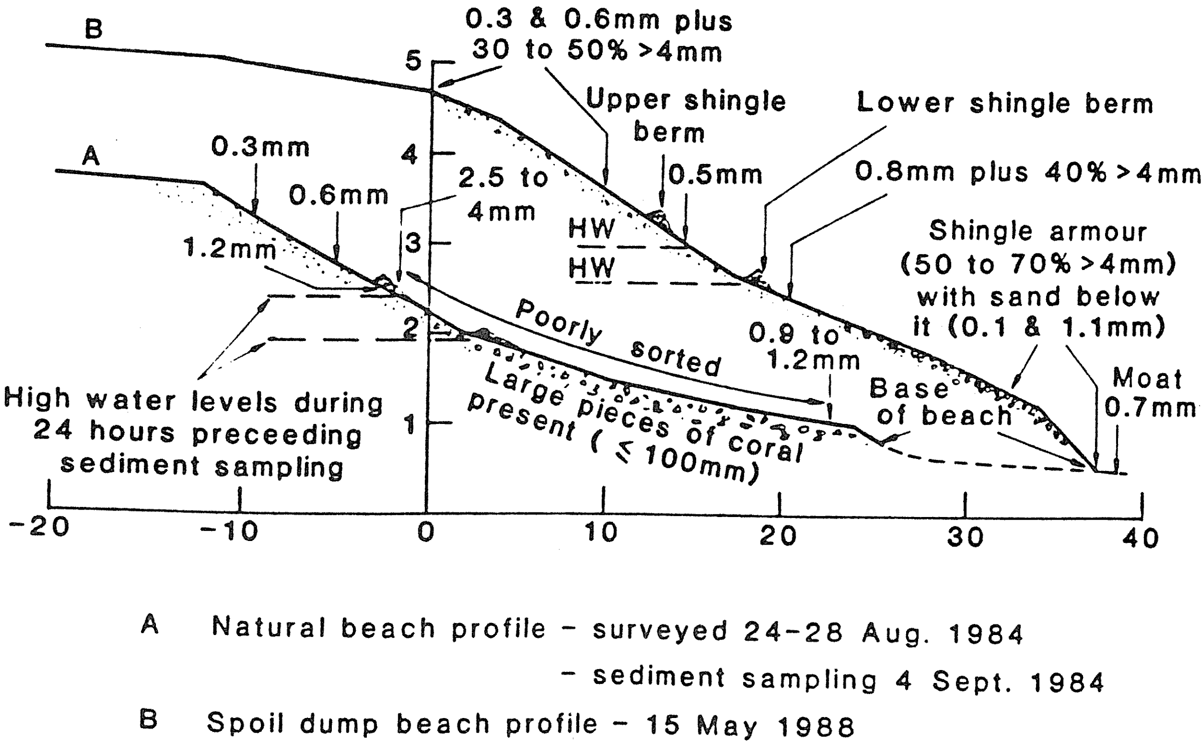


Figure 50. Comparison of natural beach profile and spoil dump beach profile

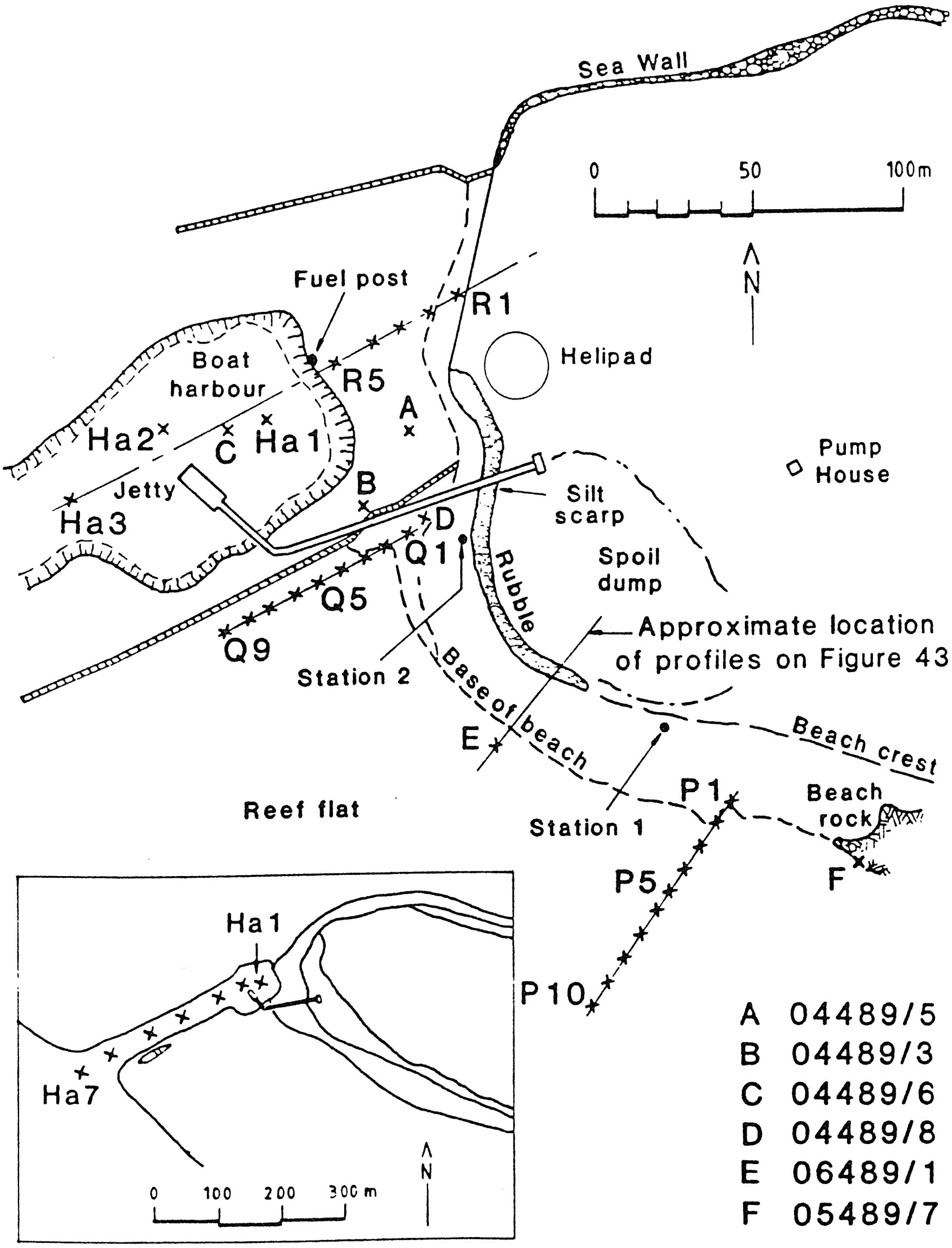


Figure 51. Sediment sample locations in vicinity of spoil dump

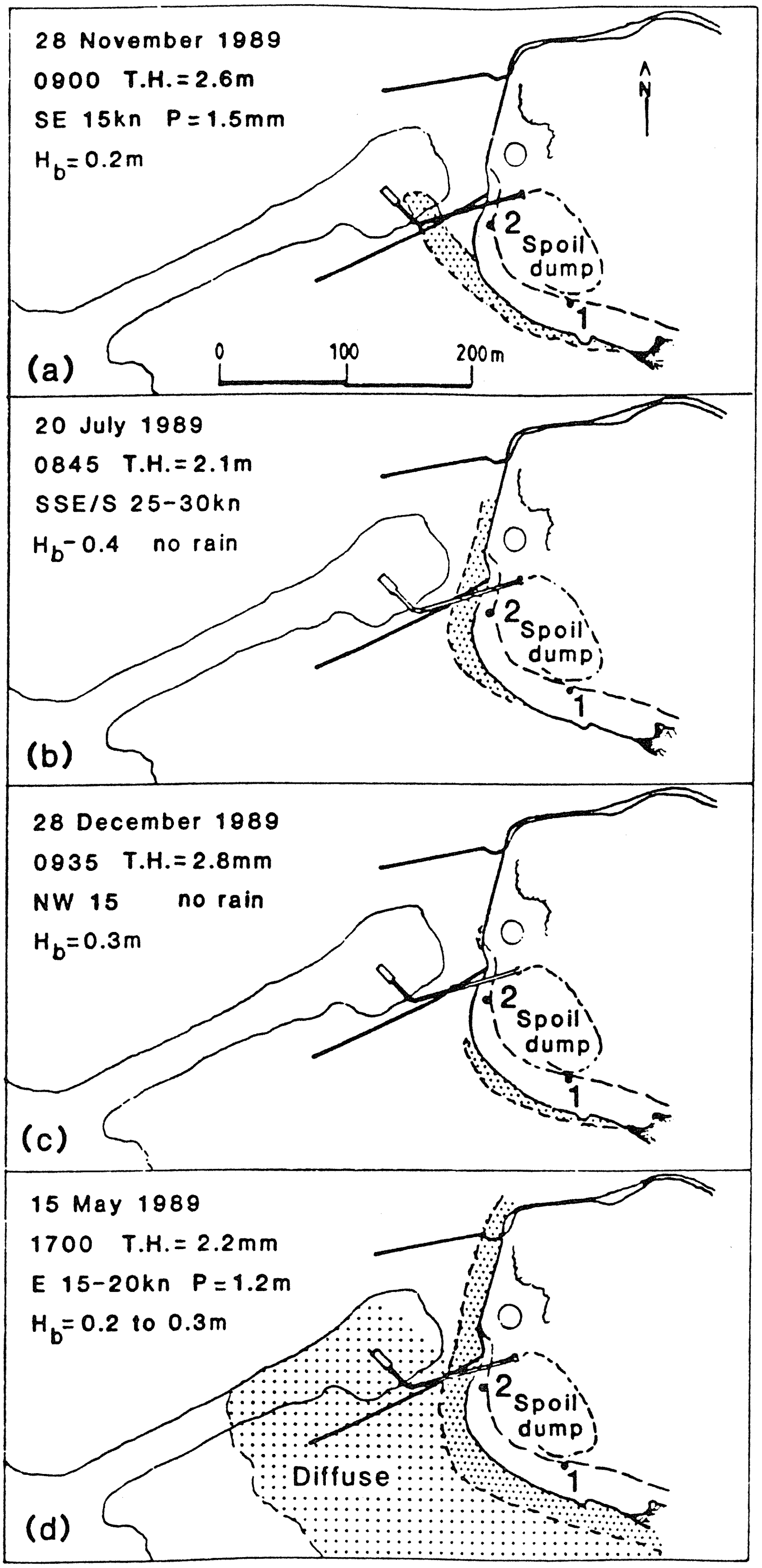


Figure 52. Silt plumes originating from spoil dump - effect of wind direction

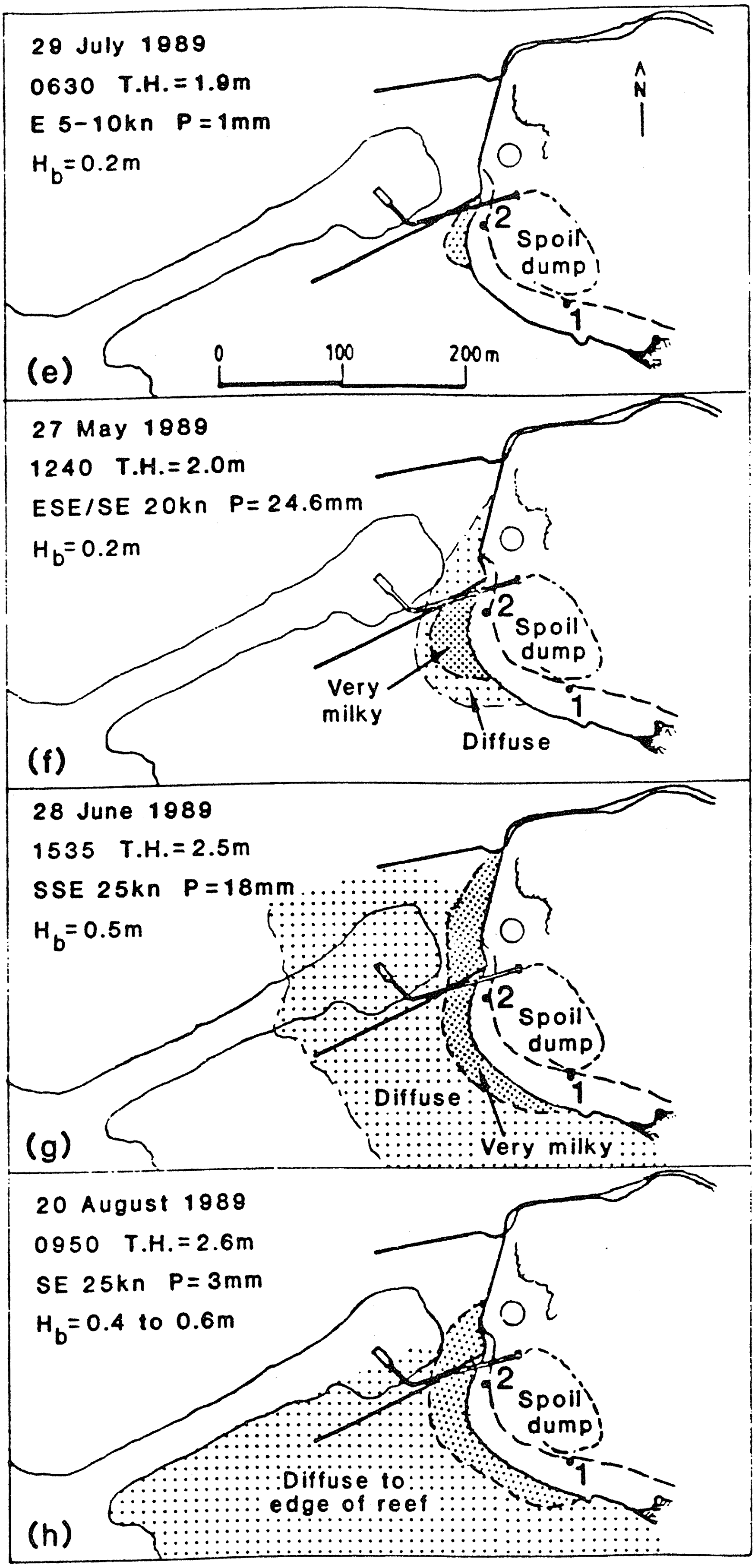


Figure 53. Silt plumes originating from spoil dump - effect of wave height and tide height.

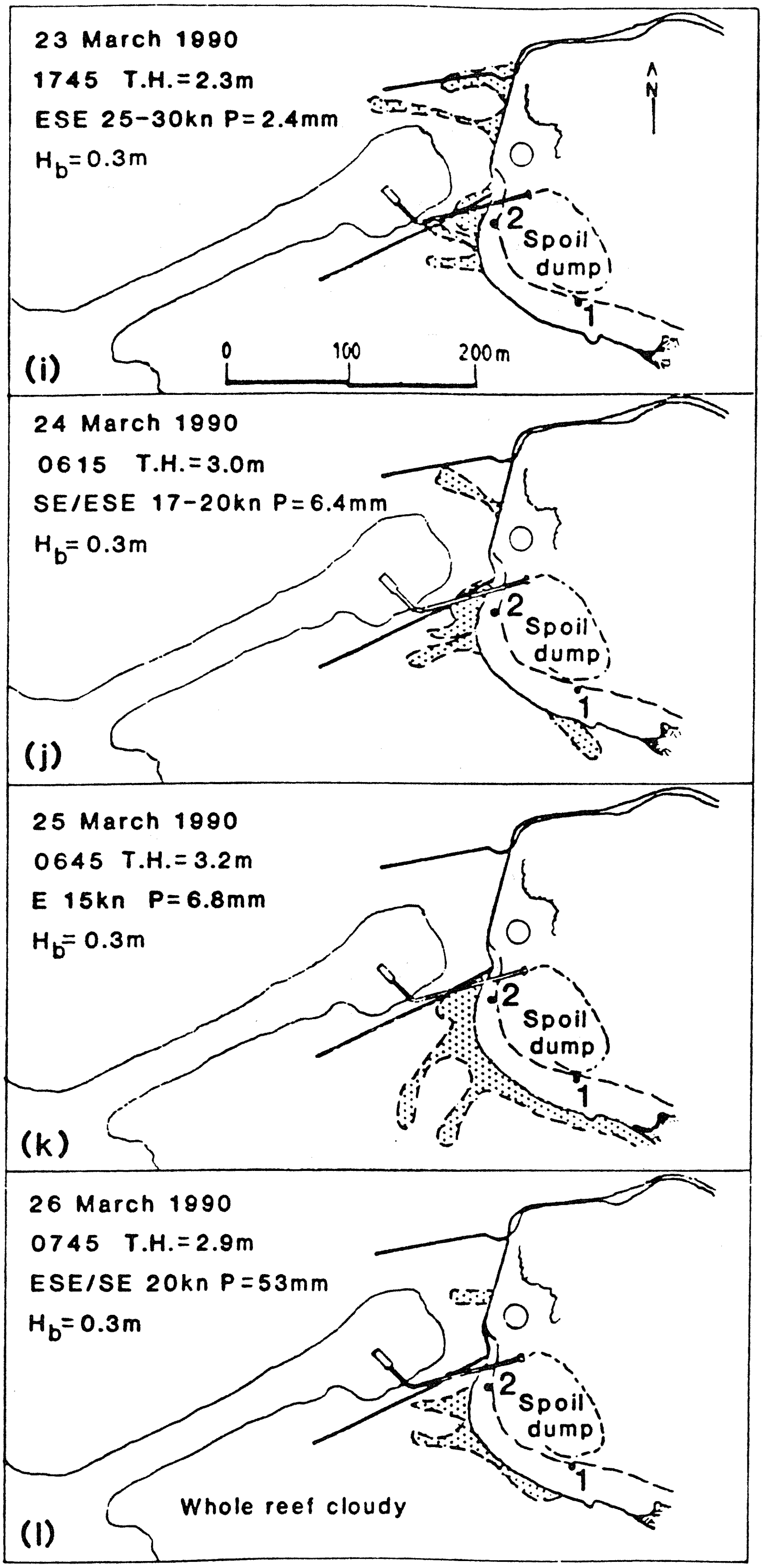


Figure 54. Silt plumes originating from spoil dump - effect of rainfall

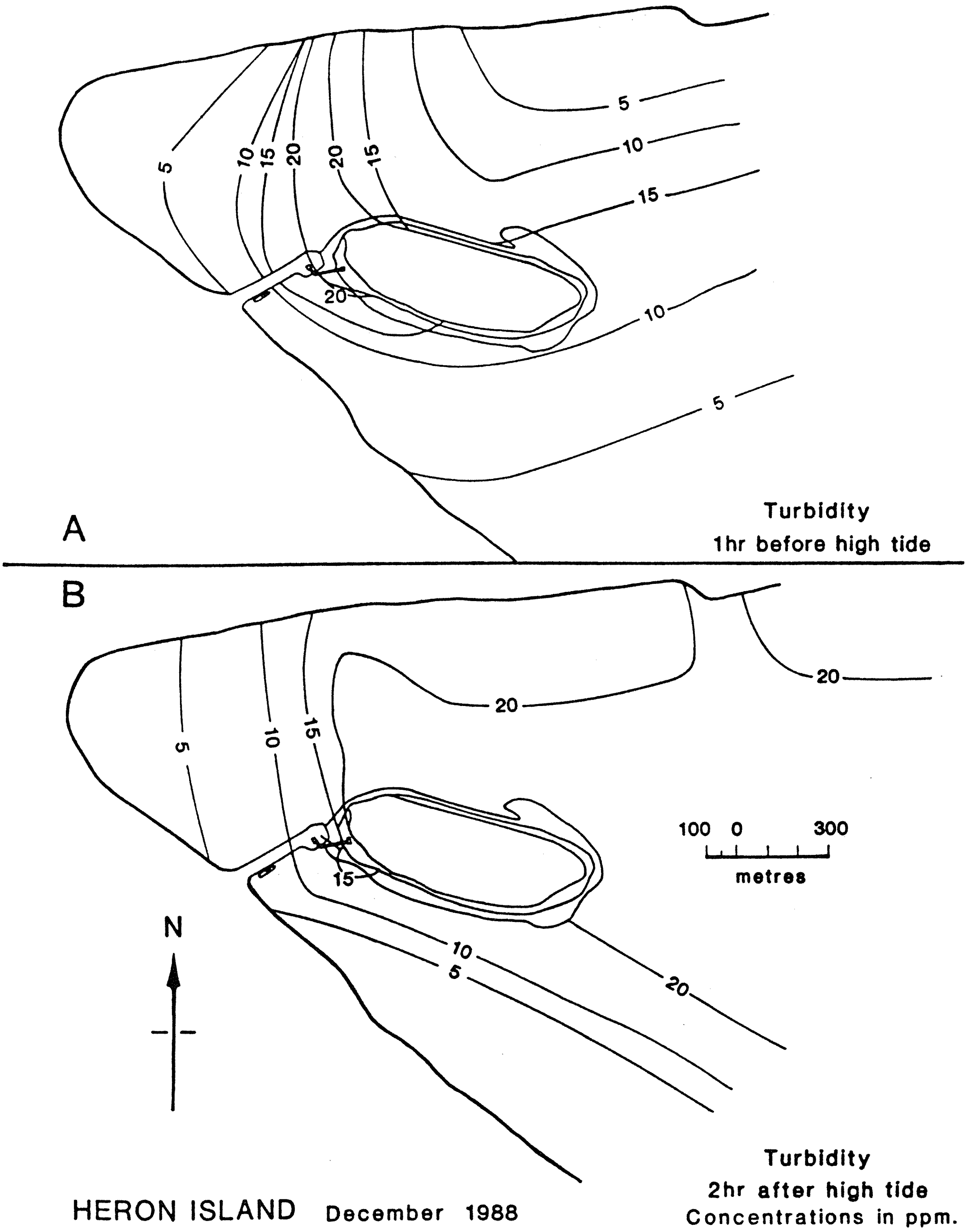


Figure 55. Silt plume concentrations - 13 December 1988

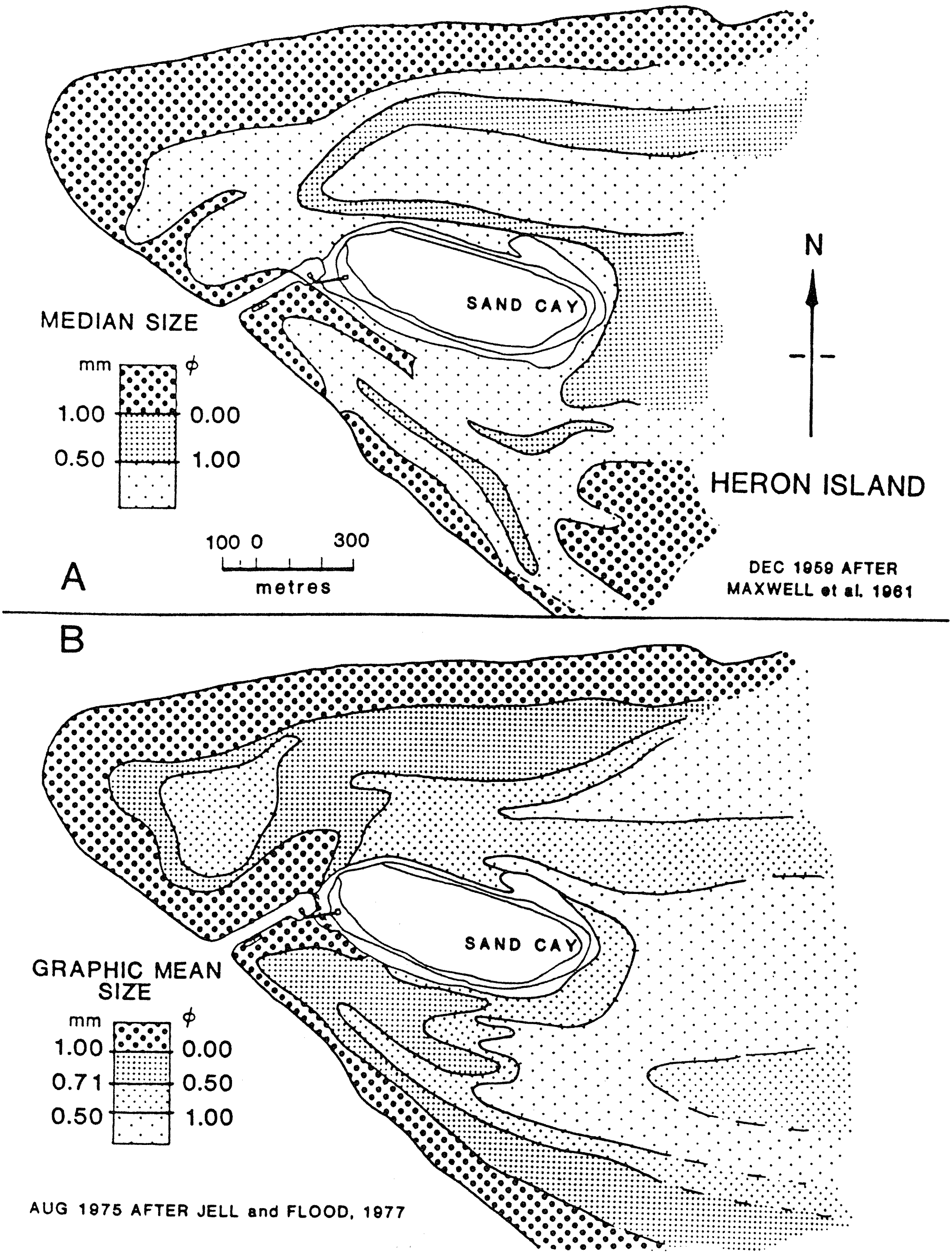


Figure 56. Distribution pattern of median size coefficients for sediments - pre 1987

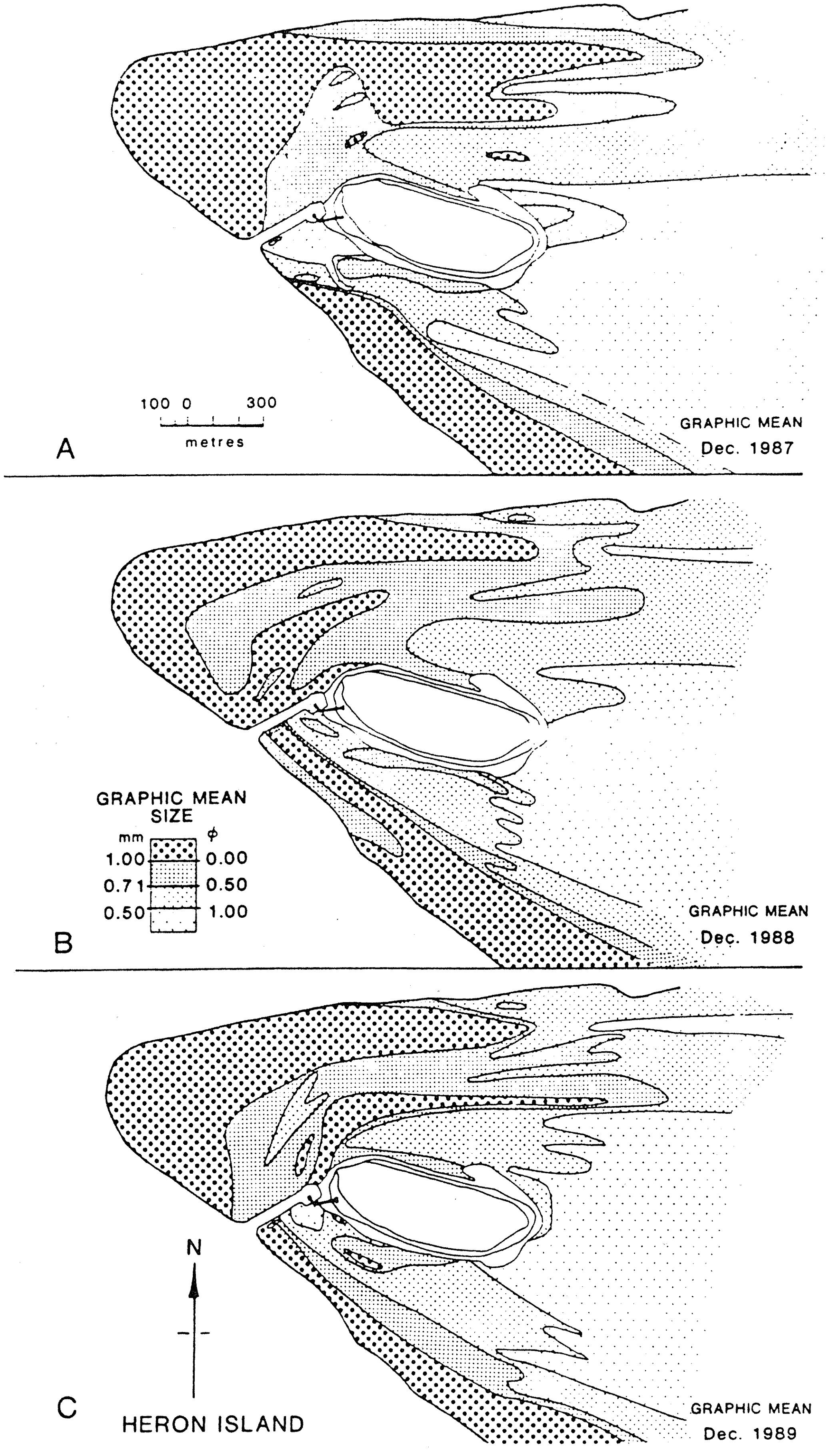


Figure 57. Distribution pattern of median size (graphic mean) coefficients for sediments - December 1987, 1988, 1989

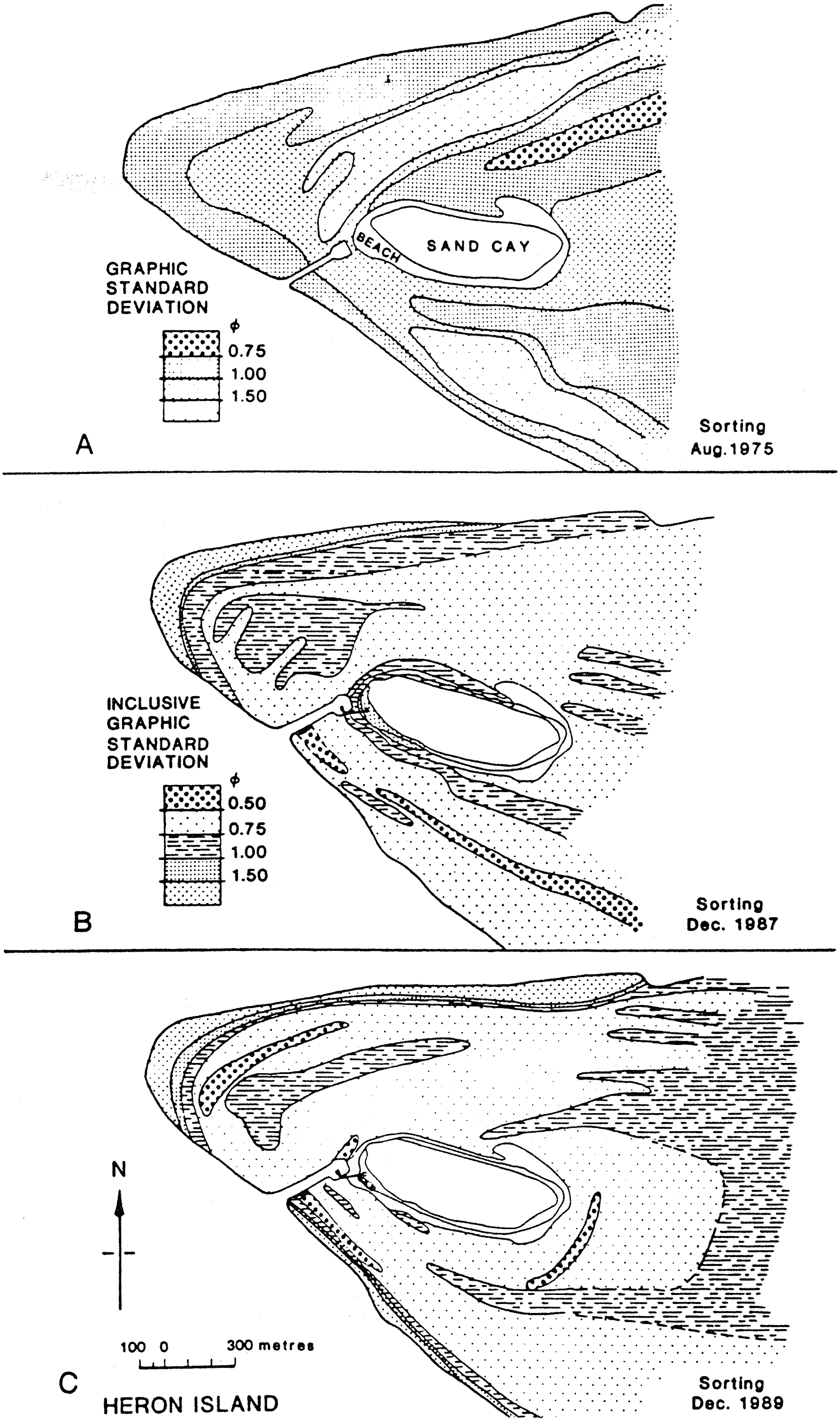


Figure 58. Distribution pattern of sorting (inclusive graphic standard deviation) coefficients for sediments - December 1987, 1988, 1989.

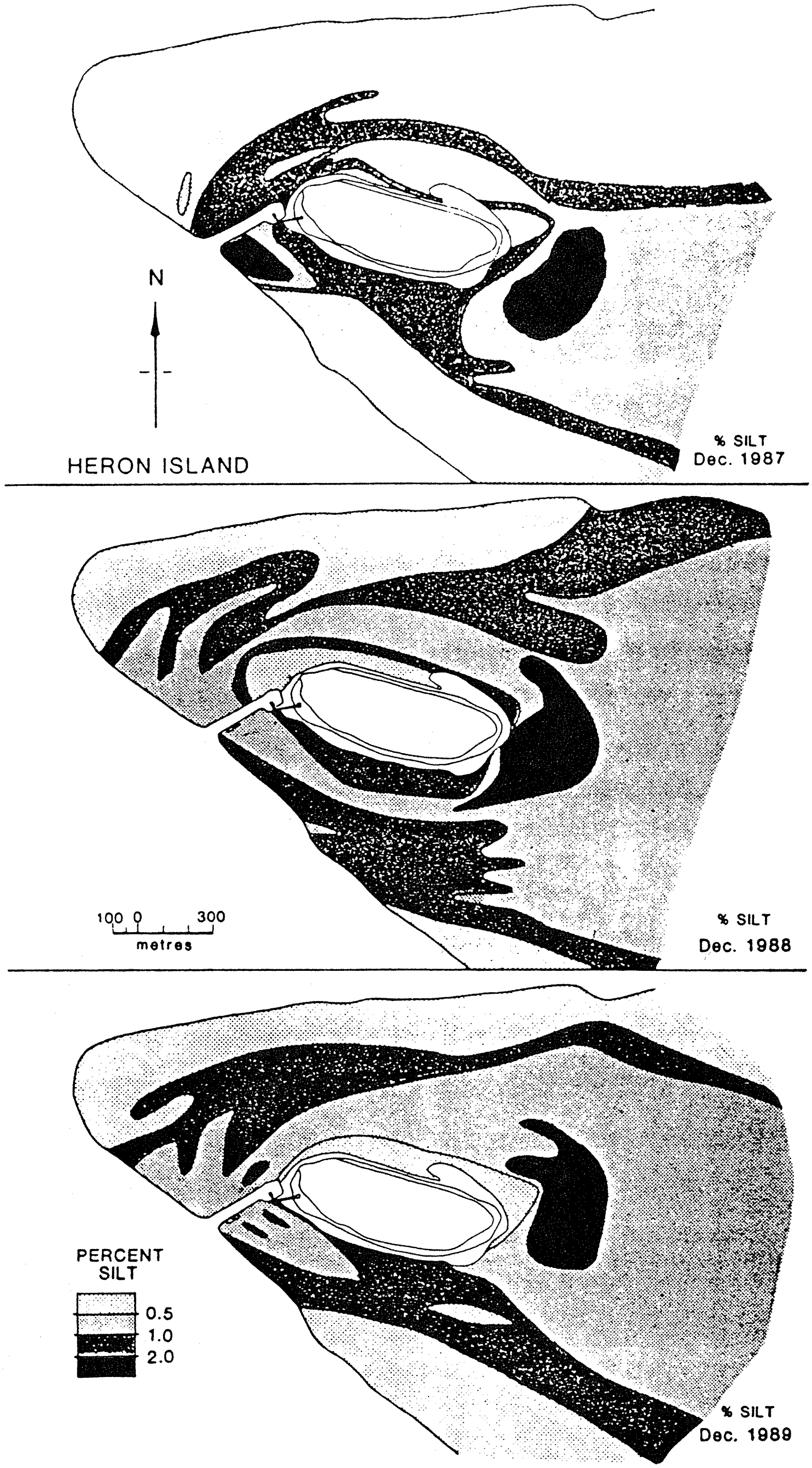


Figure 59. Distribution pattern of silt fraction (% of total sample) of sediments - December 1987, 1988, 1989.

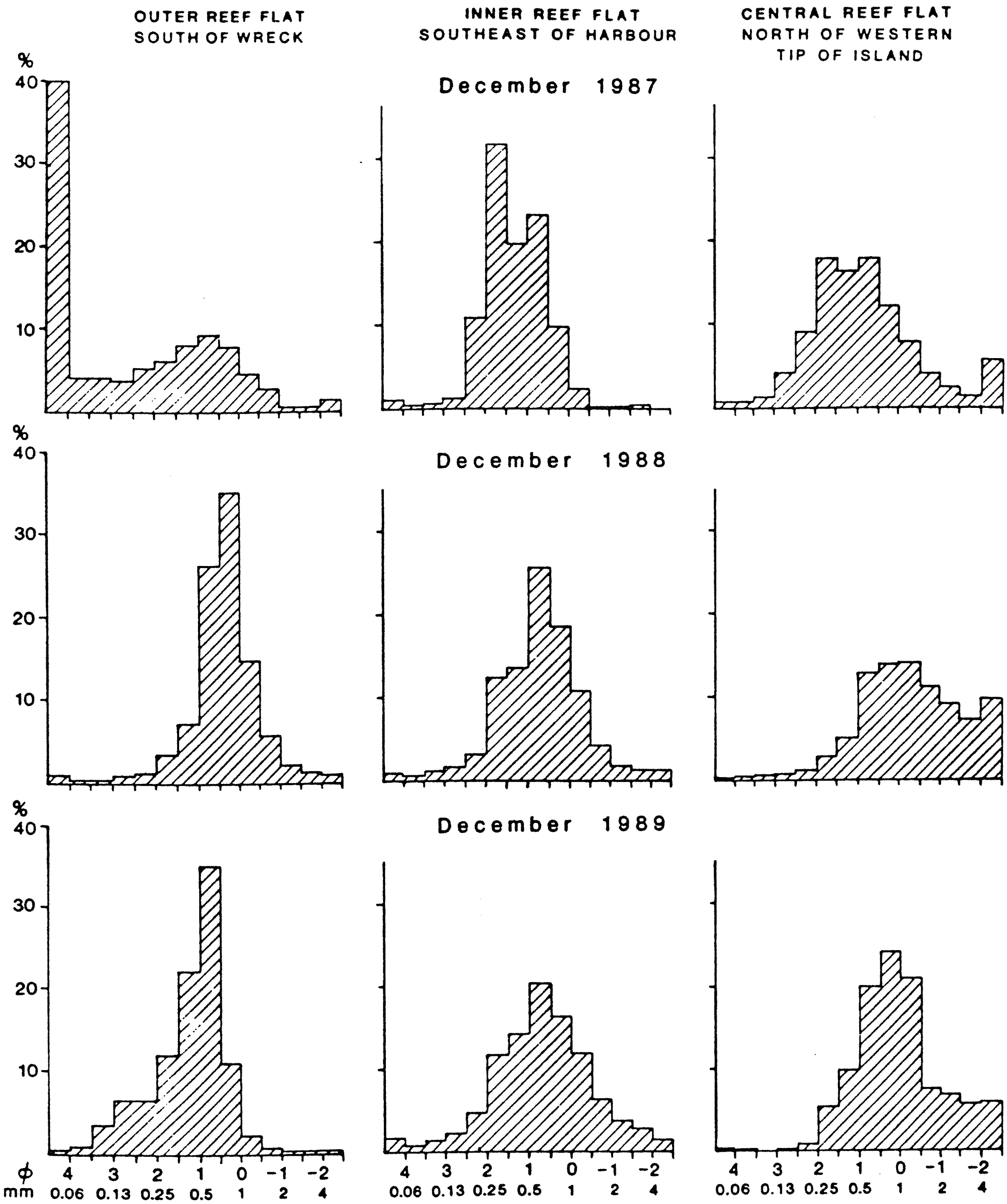


Figure 60. Histograms of size fractions of sediments - December 1987, 1988, 1989.

Appendix A

Heron Island Coastal Observations Data Recording Sheets

Name

HERON ISLAND COASTAL OBSERVATIONS

Station 1 — Day | Month | Year | using 24h clock | Time On

ARE WAVES BREAKING? few = √ many = √√ all = √√√
if white caps on reef flat, write "white caps"

Shore | Reef Flat | Reef Edge between 170° & 210°mag

TYPE OF BREAK on beach (shore)
Pl = Plunge Sp = Spill Su = Surge C = Collapse

BREAKING WAVE HEIGHT (estimate to 0.1m) Average Maximum

WAVE PERIOD eleven crests (secs)

WAVE DIRECTION (°mag)

SURF ZONE WIDTH AT BEACH (estimate in metres)
If breaking right across reef flat, put "right across"

SILT PLUME
Is there a silt plume inshore?

Is it moving to left(L), right(R) or offshore(O)?

How wide is it?

WATER MOVEMENT
Is there visible current movement in the moat?

If so, is it to left(L) or right(R)?

PRESENCE OF SCARP
Is an erosion scarp present?

Do waves reach base of scarp?

Is scarp being eroded?

Is there any evidence of accretion?

BEACH MATERIAL MOVEMENT
Are waves moving rubble(R) or sand(S) on beach?

Are waves moving rubble(R) or sand(S) at scarp foot?

COMMENT

Name

HERON ISLAND COASTAL OBSERVATIONS

Station 2
(close to jetty)

Day	Month	Year	Time on using 24h clock

ARE WAVES BREAKING ON SHORE
few = √ many = √√ all = √√√

TYPE OF BREAK on beach (shore)
Pl Plunge Sp Spill Su Surge C Collapse

BREAKING WAVE HEIGHT (estimate to 0.1m) Average Maximum

WAVE PERIOD AND DIRECTION

	Period	Direction
Main waves coming onto beach		
Subsidiary waves		

SURF ZONE WIDTH AT BEACH (estimate in metres)
If breaking right across, put "right across"

SILT PLUME
Is there a silt plume inshore?

Is it moving to left(L), right(R) or offshore(O)?

How wide is it?

PRESENCE OF SCARP
Is an erosion scarp present?

Do waves reach base of scarp?

Is scarp being eroded?

Position of scarp foot along jetty
note pile no. & no. of planks or approx. distance
If no change, put "N/C"
Is there any evidence of accretion?

BEACH MATERIAL MOVEMENT
Are waves moving rubble(R) or sand(S) on beach?

Are waves moving rubble(R) or sand(S) at scarp foot?

COMMENT

Name

HERON ISLAND COASTAL OBSERVATIONS

JETTY

Day	Month	Year	Time on using 24h clock

WIND STRENGTH estimate (knots)

WIND DIRECTION

TIDE LEVEL
From tide board (to 0.1m)

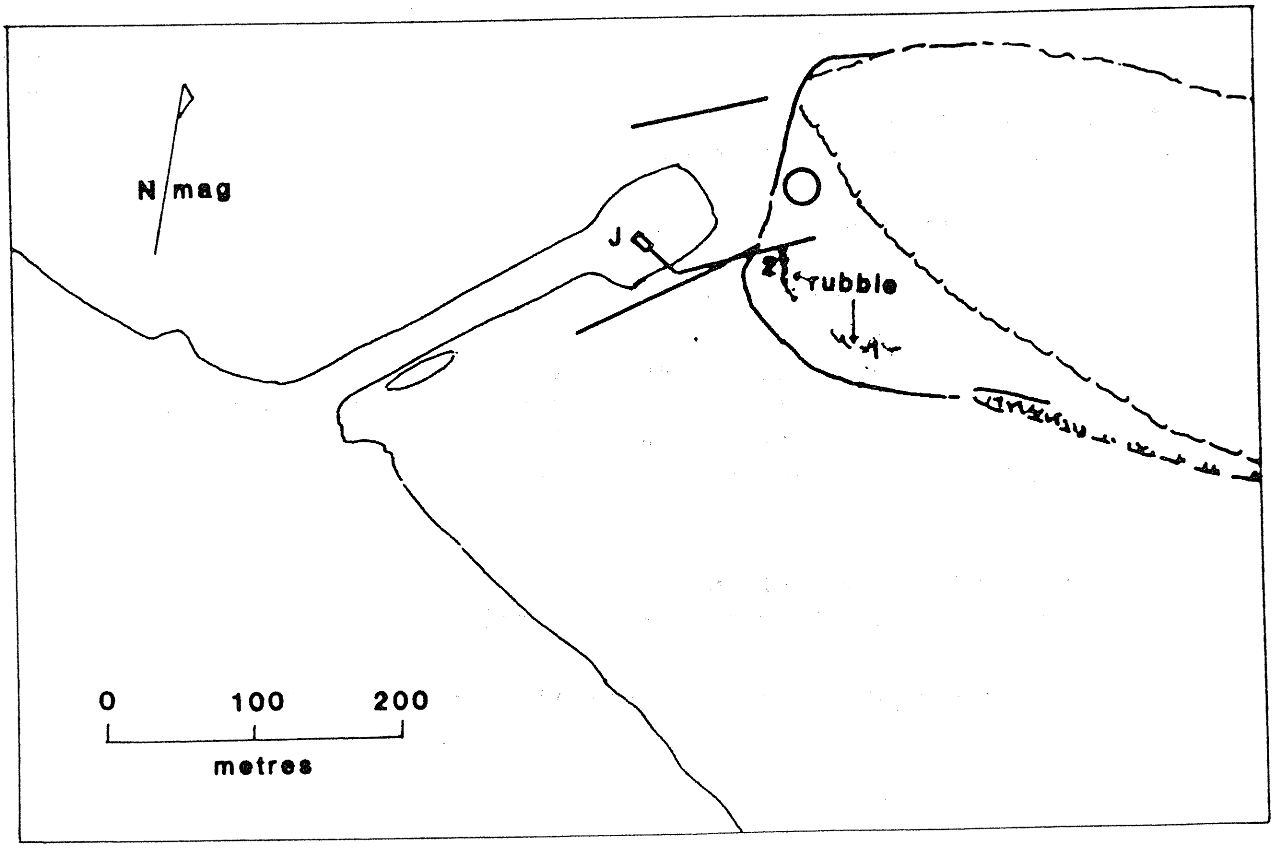
ARE WAVES BREAKING ON EDGE OF REEF?
few = √ many = √√ all = √√√
To north of jetty approx. 330° to 360° mag

WAVE PERIOD AND DIRECTION IN BOAT HARBOUR

Period	Direction

SILT PLUME
Is a silt plume present?

If so, please indicate approximate extent on sketch plan



Appendix B

Coastal Observations
May 1990 to April 1991

Figures

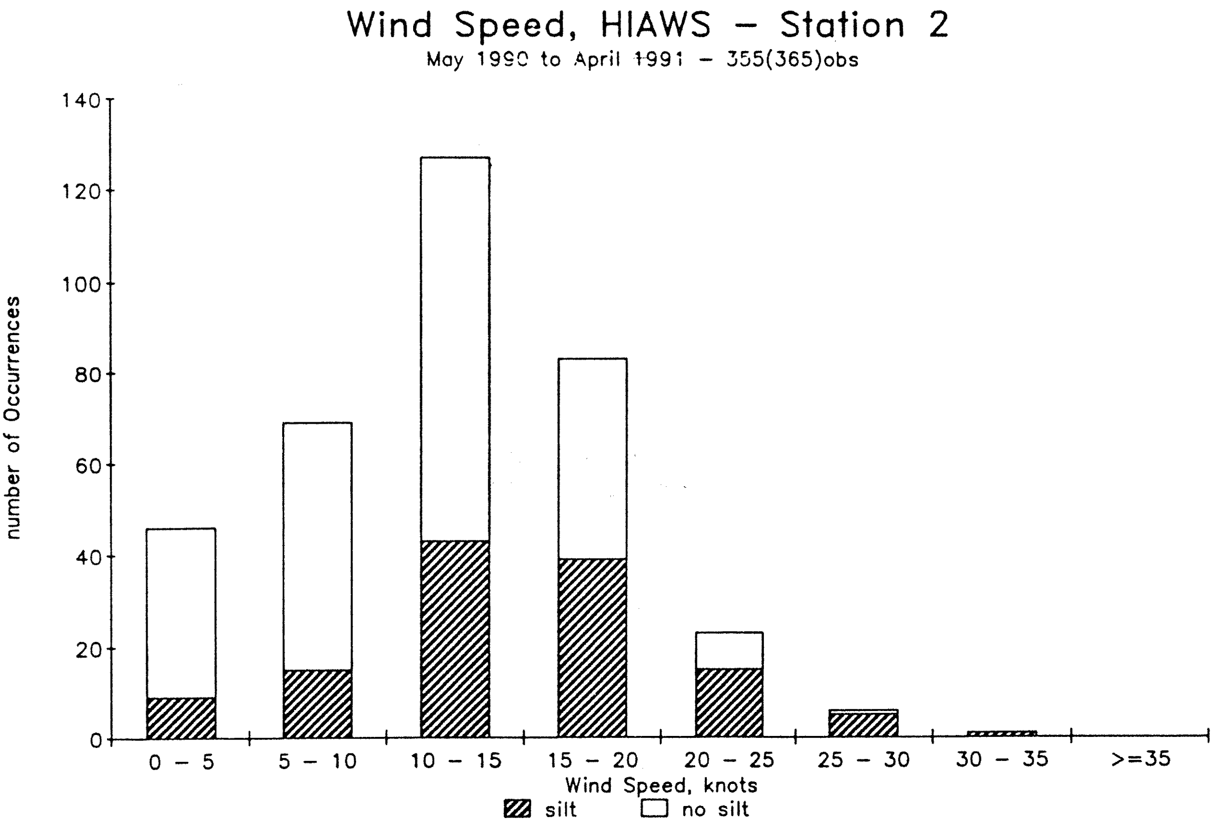


Figure B1. Silt plume occurrences and wind speed - station 2
May 1990 - April 1991

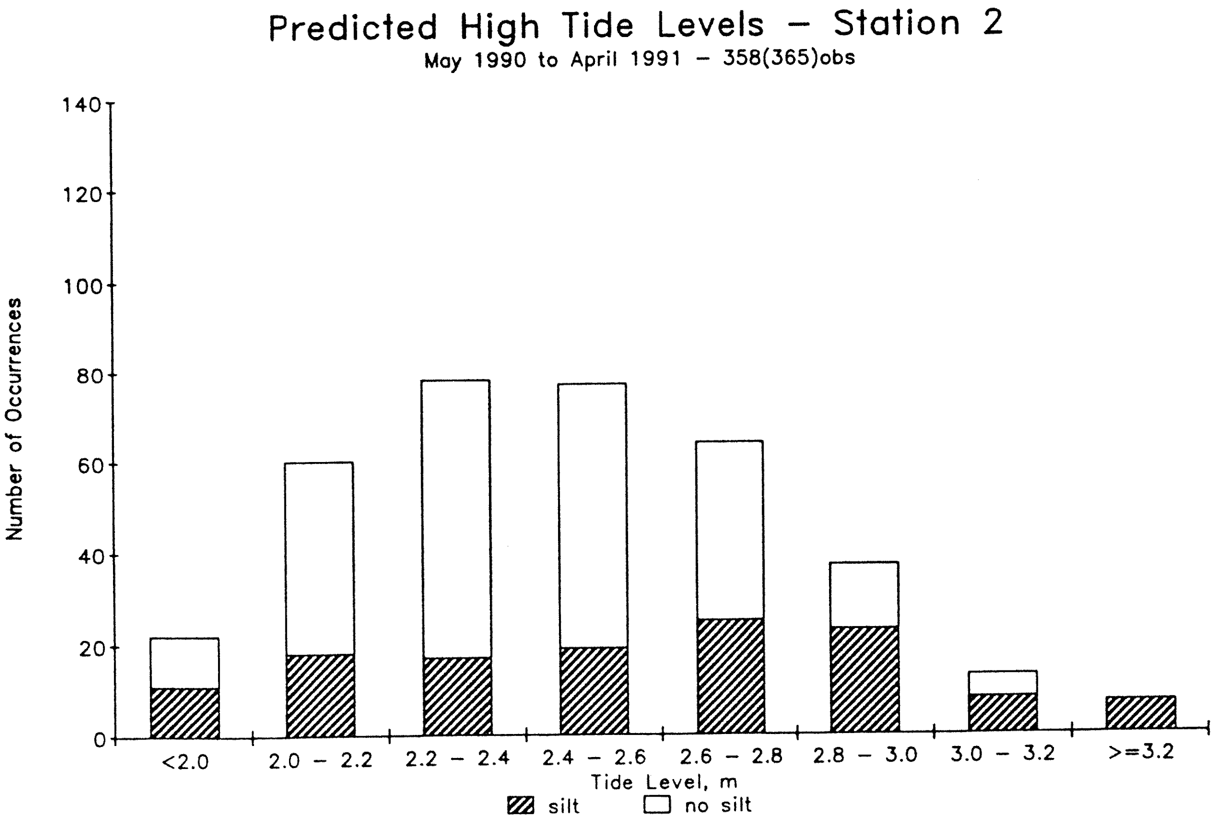


Figure B2. Silt plume occurrences and high tide level - station 2
May 1990 - April 1991

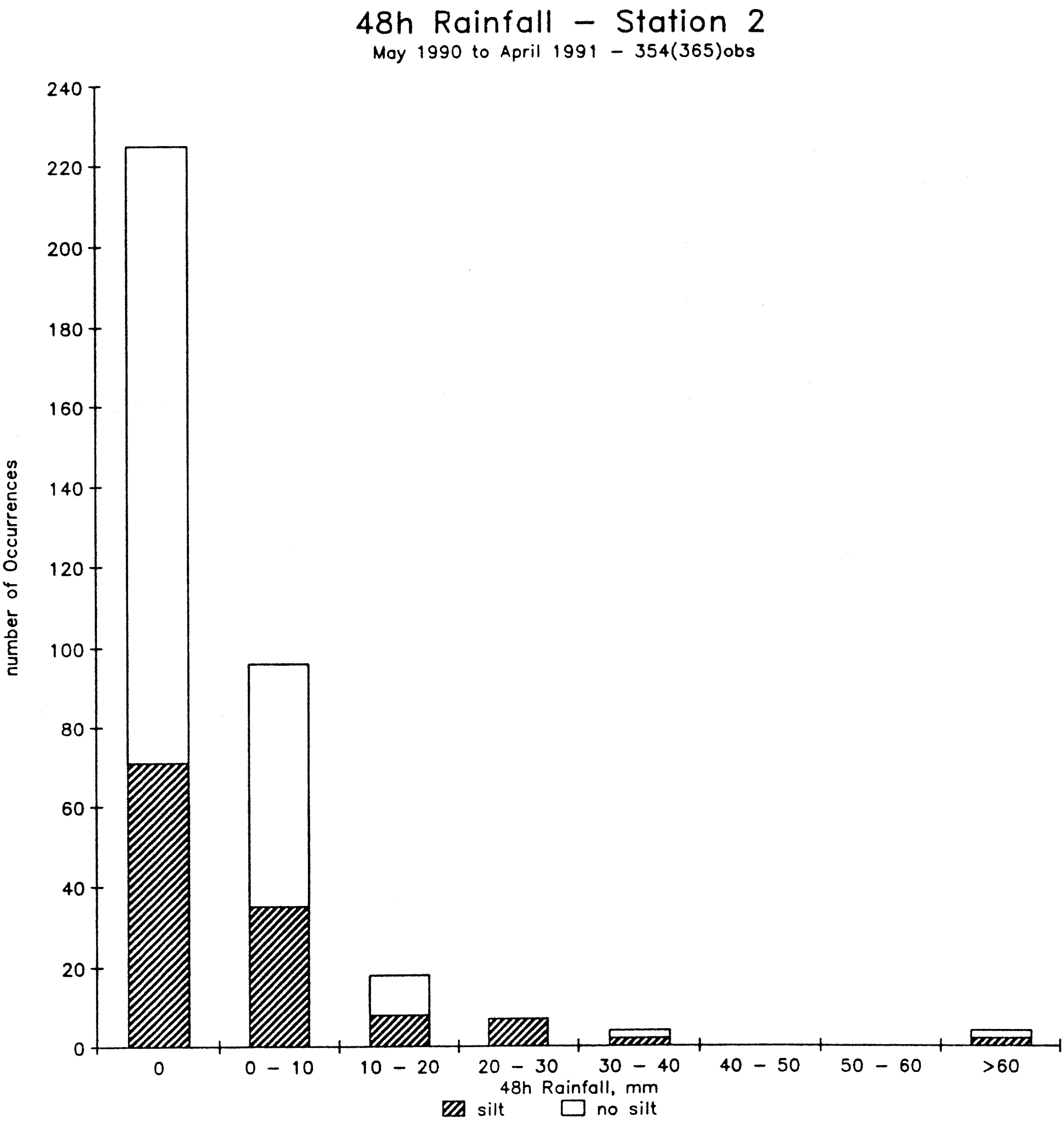


Figure B3. Silt plume occurrences and 48h rainfall - station 2
May 1990 - April 1991

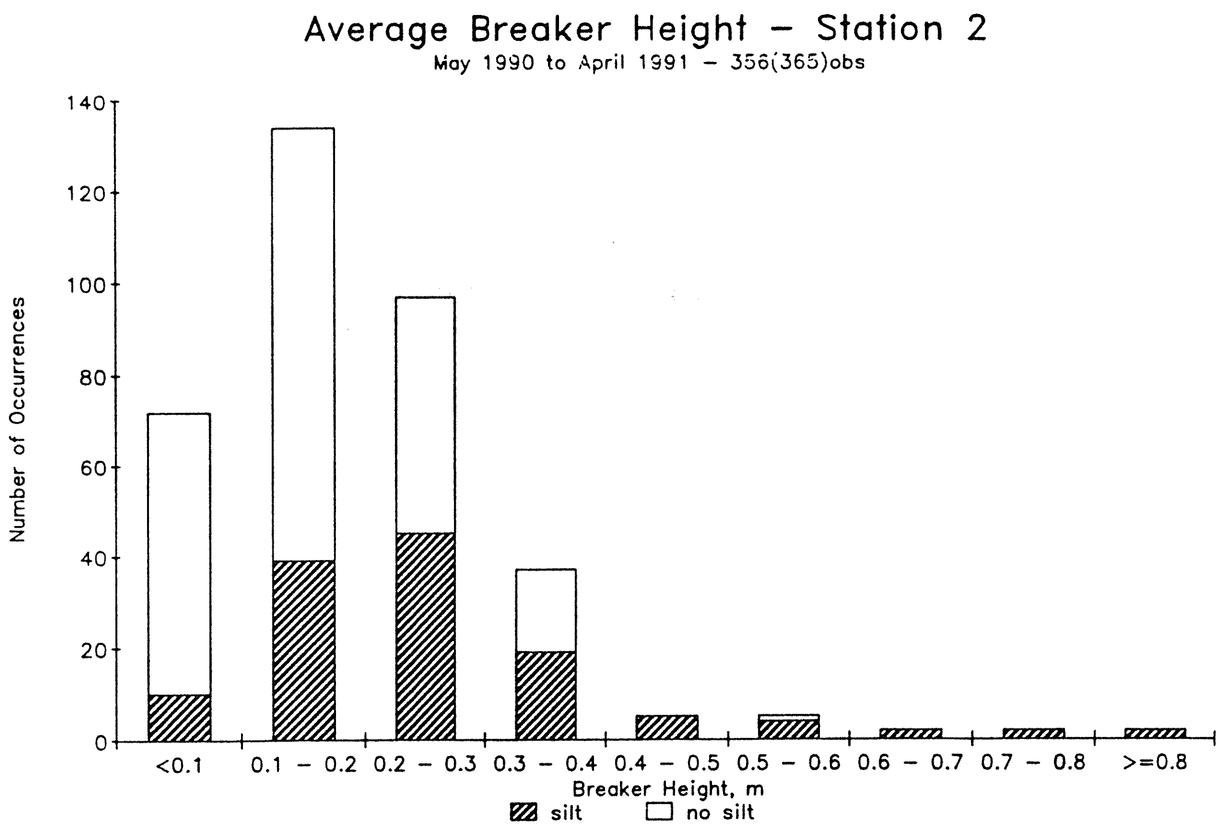


Figure B4. Silt plume occurrences and average breaker height - station 2
May 1990 - April 1991

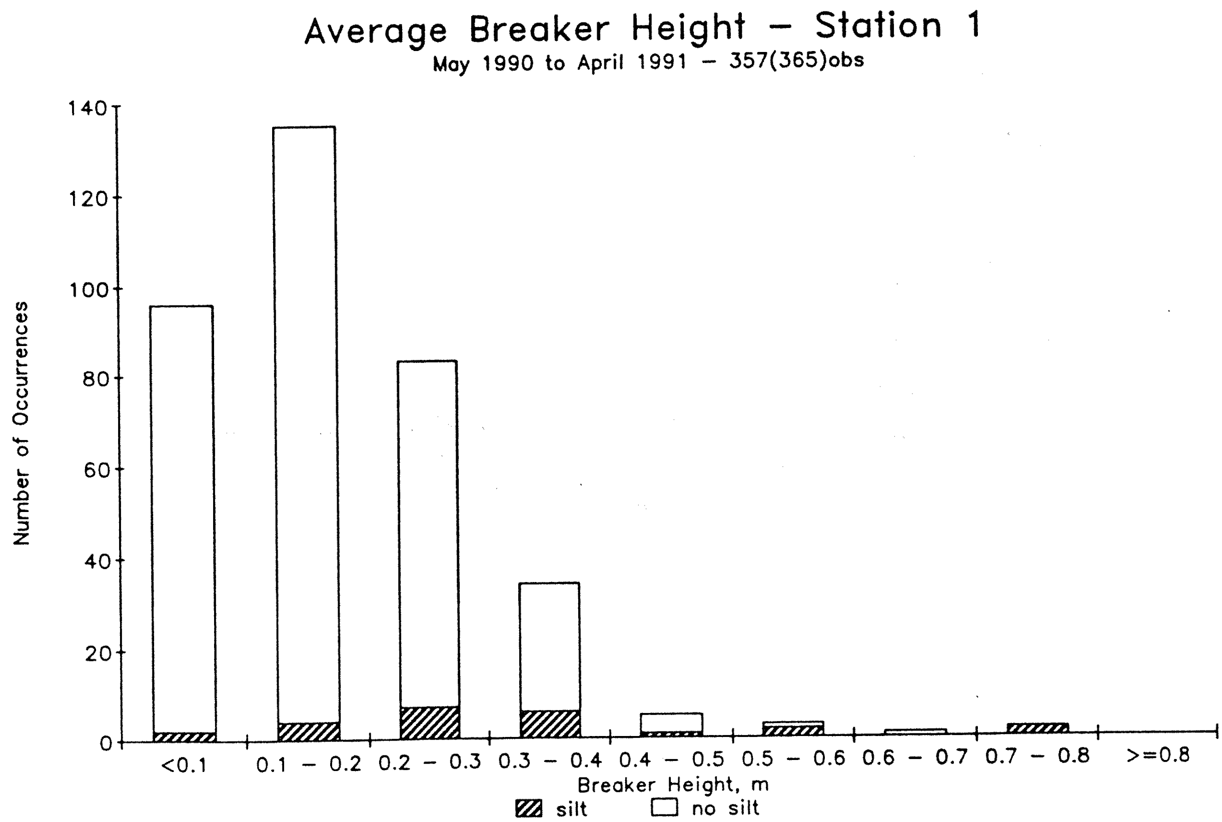


Figure B5. Silt plume occurrences and average breaker height - station 1
May 1990 - April 1991

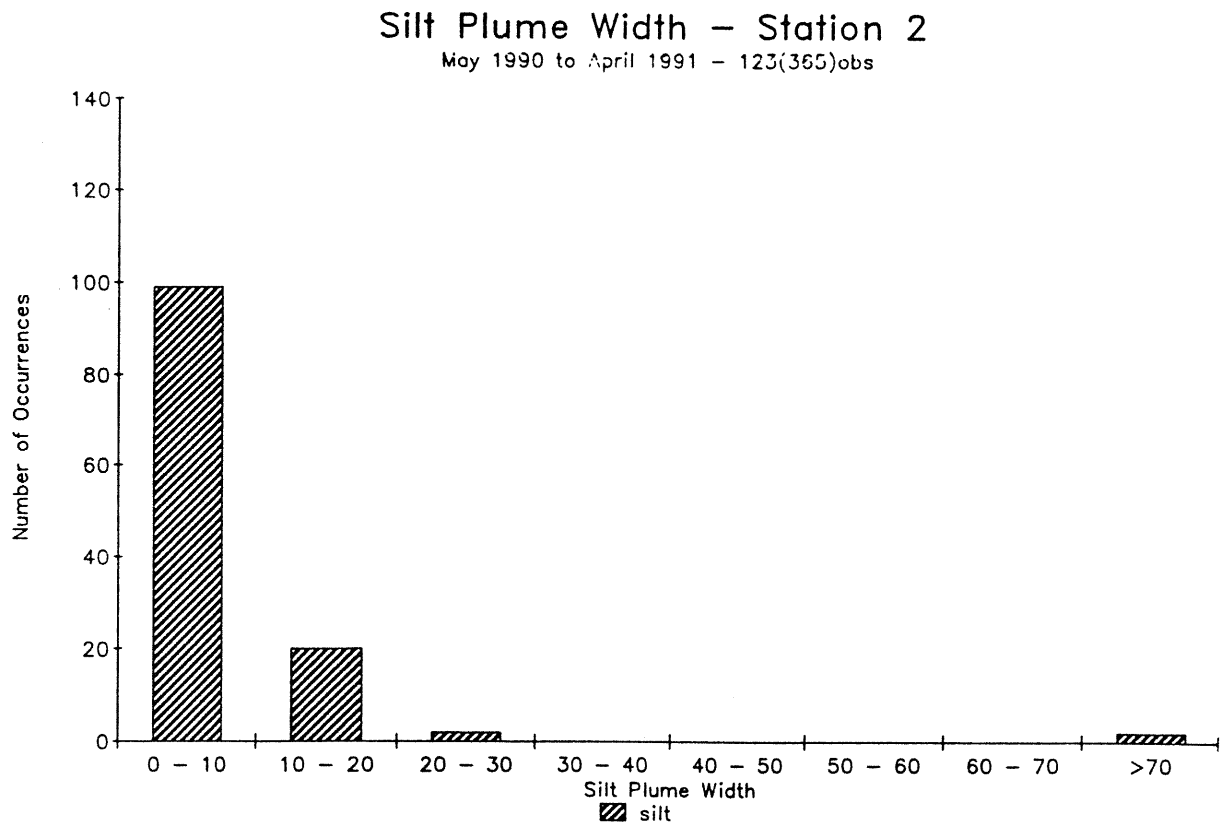


Figure B6. Silt plume widths at station 2
May 1990 - April 1991

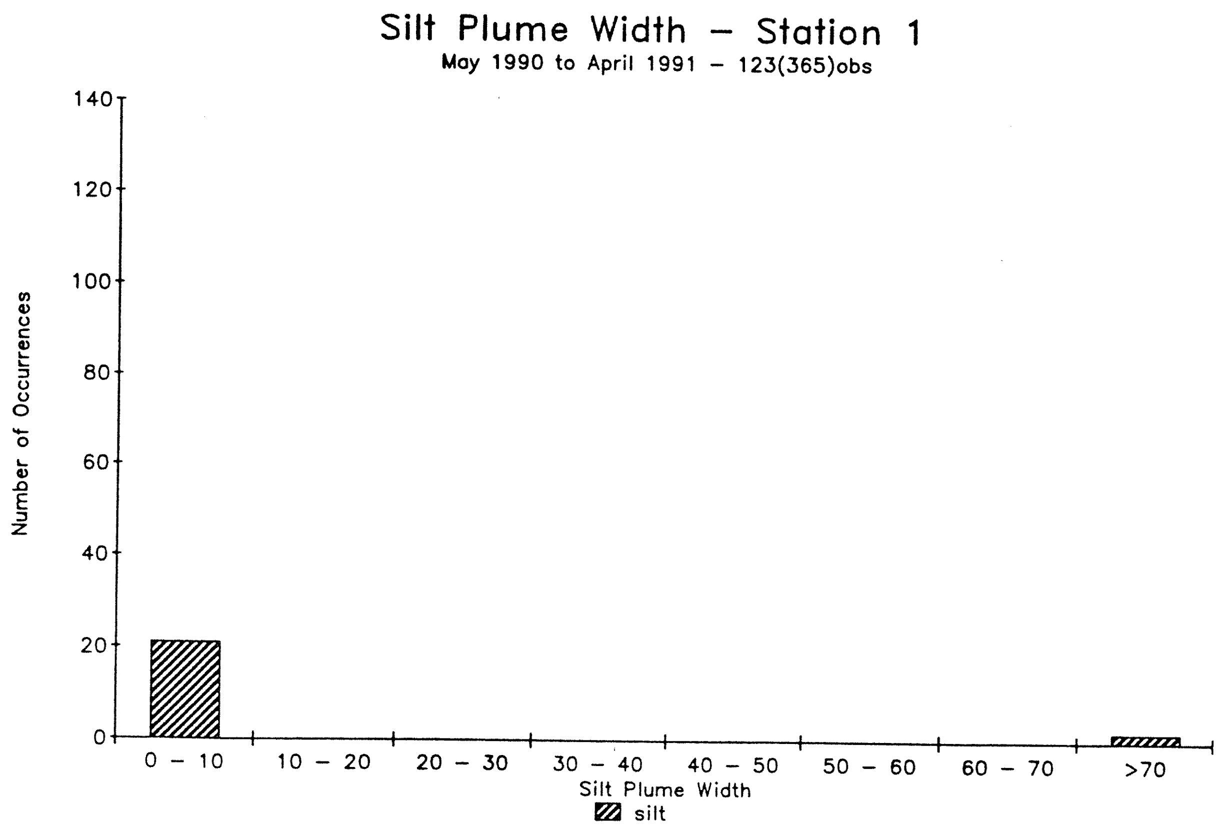


Figure B7. Silt plume widths at station 1
May 1990 - April 1991

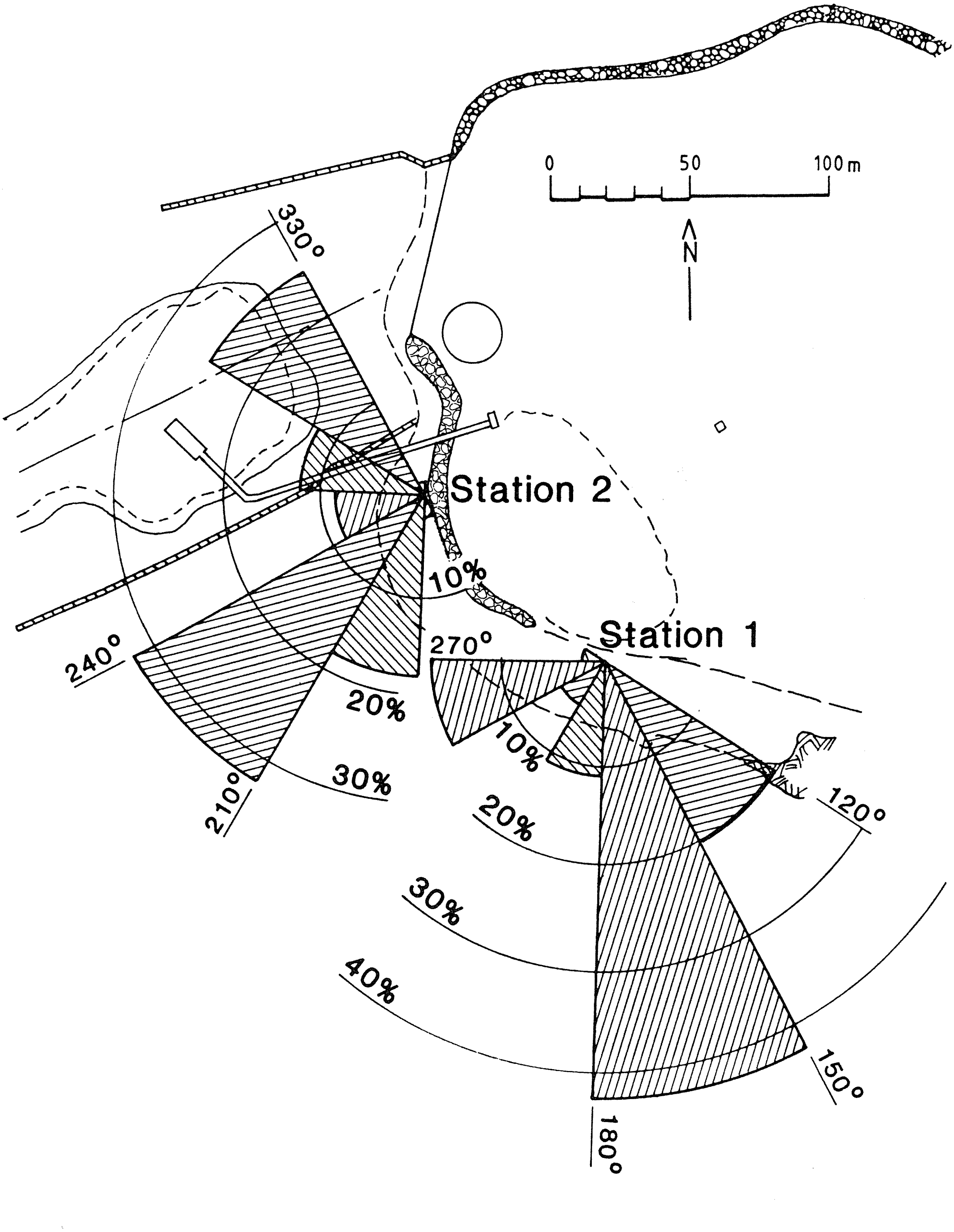


Figure B8. Wave directions at spoil dump
May 1990 - April 1991

Appendix C

Coastal Observations - Significant Events

HERON ISLAND SPOIL DUMP - COASTAL OBSERVATION

SIGNIFICANT EVENTS

SILT PLUME >=10m or WAVES >=0.4m or WIND >=20kn or RAIN >=10mm

	STATION 2			H.I.A.W.S.			DHM
DATE	SILT PLUME WIDTH m	AV. BREAKER HEIGHT m	WAVE DIR'N deg	WIND SPEED kn	WIND DIR'N deg	RAIN to 0900 mm	H.W. LEVEL m
1/12/88	N/A	N/A	N/A	**23**	37	0.0	2.3
2/12/88	N/A	N/A	N/A	17	12	**25.6**	2.3
10/12/88	N/A	0.5	55	10	42	**14.6**	2.9
12/12/88	N/A	N/A	N/A	3	100	**13.2**	2.8
13/12/88	N/A	**0.5**	205	N/A	N/A	N/A	2.8
14/12/88	N/A	**0.6**	180	N/A	N/A	N/A	2.7
15/12/88	N/A	**0.4**	180	18	124	0.4	2.6
16/12/88	N/A	**0.6**	310	**22**	110	2.6	2.5
17/12/88	N/A	**0.4**	145	N/A	N/A	N/A	2.4
18/12/88	N/A	**0.7**	260	14	315	**73.8**	2.3
21/12/88	N/A	N/A	N/A	4	22	**22.8**	2.9
14/1/89	N/A	N/A	N/A	**24**	125	2.0	2.5
15/1/89	N/A	N/A	N/A	**26**	127	0.0	2.3
16/1/89	N/A	N/A	N/A	**20**	112	0.4	2.1
25/1/89	N/A	**0.8**	225	16	98	**16.4**	2.7
26/1/89	N/A	0.3	225	**21**	111	3.2	2.6
27/1/89	N/A	**0.6**	225	19	135	0.6	2.5
4/2/89	N/A	**0.4**	320	14	96	0.4	2.9
5/2/89	N/A	**1.0**	325	13	340	**207.4**	3.1
6/2/89	N/A	**0.5**	190	19	148	5.6	3.2
8/2/89	N/A	**1.0**	220	19	111	8.4	3.2
13/2/89	N/A	0.0	215	**22**	135	0.2	2.0
14/2/89	N/A	0.0	210	**23**	118	0.2	1.9
15/2/89	N/A	0.0	200	**23**	117	0.6	2.0
16/2/89	N/A	**1.0**	220	**23**	124	0.0	2.7
17/2/89	N/A	0.3	230	**22**	128	0.0	2.8
18/2/89	N/A	**0.5**	215	18	125	0.0	2.9
25/2/89	N/A	0.0	220	**22**	135	4.0	2.4
26/2/89	N/A	0.0	205	**22**	125	3.6	2.2

	STATION 2			H.I.A.W.S.			DHM	
DATE	SILT PLUME WIDTH	AV. BREAKER HEIGHT	WAVE DIR'N	WIND SPEED	WIND DIR'N	RAIN to 0900	H.W. LEVEL	
	m	m	deg	kn	deg	mm	m	
28/2/89	N/A	0.0	220	13	132	**11.0**	1.9	
1/3/89	N/A	0.0	205	**20**	138	7.4	1.8	
2/3/89	N/A	0.0	215	**22**	125	4.0	1.9	
3/3/89	N/A	0.0	190	18	96	**40.2**	2.1	
4/3/89	N/A	0.0	190	**20**	106	**20.6**	2.3	
5/3/89	N/A	0.0	205	15	90	**23.8**	2.5	
19/3/89	N/A	0.1	300	12	81	**45.4**	2.8	
30/3/89	N/A	N/A	N/A	18	85	**29.2**	1.8	
2/4/89	N/A	0.3	290	14	70	**18.0**	2.4	
4/4/89	**80**	**0.4**	300	**20**	84	0.0	3.0	
5/4/89	**50**	**0.4**	310	**24**	60	1.0	3.0	
6/4/89	5	**0.4**	330	15	77	0.6	3.0	
7/4/89	**20**	**0.4**	300	14	84	4.0	2.9	
8/4/89	**20**	0.2	300	12	95	1.4	2.7	
9/4/89	**20**	0.1	300	15	93	0.4	2.4	
10/4/89	**20**	0.1	270	9	100	**18.4**	2.1	
13/4/89	**10**	0.1	280	2	35	0.0	1.9	
17/4/89	**20**	0.2	250	2	97	0.0	2.6	
20/4/89	**10**	0.3	220	15	127	2.0	2.6	
21/4/89	**10**	0.2	280	11	100	**11.4**	2.5	
22/4/89	N/A	0.3	265	12	108	**15.2**	2.4	
23/4/89	5	0.2	290	11	71	**25.6**	2.3	
24/4/89	**20**	0.2	290	17	39	**25.6**	2.2	
25/4/89	**20**	**0.4**	275	18	285	**22.8**	2.1	
27/4/89	**10**	0.3	255	15	255	0.0	1.9	*1
3/5/89	**10**	**0.4**	290	9	80	0.0	2.8	
4/5/89	3	0.3	280	5	65	**17.8**	2.8	
7/5/89	5	0.2	270	10	85	**17.4**	2.4	
8/5/89	6	0.3	290	13	100	**43.4**	2.2	
15/5/89	**20**	0.3	260	13	80	1.2	2.4	
16/5/89	**20**	**0.4**	300	16	75	1.0	2.5	
17/5/89	**20**	**0.4**	312	17	75	**23.2**	2.4	
18/5/89	**50**	**0.4**	265	19	110	**14.2**	2.4	*2
19/5/89	**20**	0.3	310	13	90	0.4	2.4	
20/5/89	**15**	0.3	230	18	130	0.4	2.3	
21/5/89	**10**	**0.4**	235	**24**	130	6.0	2.3	
22/5/89	**20**	0.2	270	18	105	7.8	2.2	

*1 Salt water pipe trench excavated 26/4/89.
*2 Probable human disturbance to beach, but not recorded.

DATE	STATION 2 SILT PLUME WIDTH m	STATION 2 AV. BREAKER HEIGHT m	STATION 2 WAVE DIR'N deg	H.I.A.W.S. WIND SPEED kn	H.I.A.W.S. WIND DIR'N deg	H.I.A.W.S. RAIN to 0900 mm	DHM H.W. LEVEL m	
26/5/89	3	0.1	275	17	70	**27.2**	2.0	
27/5/89	**10**	0.2	275	17	95	**24.6**	2.1	
28/5/89	**25**	0.3	N/A	**30**	130	**33.2**	2.2	*3
29/5/89	**70**	**0.5**	220	**22**	140	4.6	2.4	*3
30/5/89	**10**	**0.5**	307	11	135	8.8	2.6	
31/5/89	4	**0.5**	280	11	255	0.0	2.8	
1/6/89	3	**0.4**	230	6	160	0.0	2.9	
7/6/89	**15**	0.3	220	16	155	0.0	2.1	
13/6/89	**10**	0.3	225	18	134	0.0	2.3	
15/6/89	**15**	0.3	250	18	133	0.0	2.6	
27/6/89	3	**0.4**	235	18	135	0.0	2.4	
28/6/89	5	**0.5**	235	18	125	0.6	2.6	
29/6/89	**15**	**0.6**	307	18	120	**17.6**	2.7	
30/6/89	8	**0.5**	305	14	128	**13.6**	2.9	
11/7/89	0	0.2	235	13	175	**14.8**	2.1	
19/7/89	6	**0.4**	235	18	185	0.0	2.3	
20/7/89	4	**0.4**	235	16	195	0.0	2.4	
23/7/89	**10**	0.2	295	4	50	0.2	2.5	
26/7/89	**15**	0.2	220	16	132	0.0	2.4	
27/7/89	**30**	**0.5**	245	**22**	130	0.0	2.5	
28/7/89	**20**	0.3	310	14	110	1.4	2.6	
1/8/89	3	0.3	233	**21**	164	0.0	2.3	
13/8/89	0	**0.4**	265	12	130	0.0	2.6	
18/8/89	5	**0.5**	162	19	160	**10.4**	2.6	
19/8/89	**300**	**0.7**	235	**22**	105	**15.8**	2.7	*4
20/8/89	**300**	**0.6**	220	**21**	134	3.0	2.7	*4
23/8/89	**10**	0.2	230	3	317	0.0	2.4	
24/8/89	**10**	0.1	320	6	133	0.0	2.4	
27/8/89	0	**0.4**	311	10	330	0.0	2.7	
2/9/89	**20**	0.3	235	**23**	141	0.0	2.5	
9/9/89	**13**	N/A	220	12	110	0.0	2.2	
18/9/89	2	**0.5**	310	15	308	0.0	2.9	*5
19/9/89	4	**0.5**	302	11	295	0.0	2.8	

*3 Beach area and scarp reshaped by earthmoving equipment causing very thick silt plume, especially under jetty.
*4 Silt plume to edge of reef.
*5 Scarp erosion, tractor activity

	STATION 2			H.I.A.W.S.			DHM
DATE	SILT PLUME WIDTH	AV. BREAKER HEIGHT	WAVE DIR'N	WIND SPEED	WIND DIR'N	RAIN to 0900	H.W. LEVEL
	m	m	deg	kn	deg	mm	m
27/9/89	**10**	0.3	224	**25**	145	0.0	2.4
29/9/89	5	**0.4**	298	18	116	0.0	2.6
30/9/89	**20**	0.3	210	12	115	0.0	2.6
10/10/89	**10**	**0.4**	310	17	310	0.0	2.6
28/10/89	N/A	0.2	210	**26**	153	1.2	2.6
7/11/89	5	0.2	195	11	110	**12.8**	2.4
20/11/89	0	0.1	195	**21**	113	**14.8**	2.4
21/11/89	0	0.2	140	**26**	122	0.0	2.3
28/11/89	**14**	0.1	200	12	96	1.4	2.8
29/11/89	**10**	0.2	310	15	104	0.0	2.8
15/12/89	**12**	0.2	220	19	124	**40.2**	3.0
17/12/89	**11**	0.2	210	**23**	103	0.4	2.7
18/12/89	**10**	0.3	220	**22**	118	5.4	2.5
23/1/90	6	0.3	220	**22**	110	0.0	2.6
24/1/90	5	0.3	210	**23**	125	5.0	2.7
30/1/90	**15**	0.3	220	**22**	114	0.0	3.0
31/1/90	**10**	0.3	230	17	144	0.0	2.8
25/2/90	**20**	0.3	185	14	107	0.0	3.1
26/2/90	**10**	0.3	205	**25**	128	6.6	3.1
27/2/90	**14**	**0.4**	N/A	**20**	118	**21.0**	3.1
4/3/90	0	0.0	N/A	17	88	**15.8**	1.9
5/3/90	0	0.1	170	**22**	100	**21.0**	2.0
6/3/90	0	0.1	N/A	**20**	133	0.4	2.2
8/3/90	**10**	**0.4**	230	**23**	171	0.0	2.9
13/3/90	4	0.2	225	**20**	123	0.2	2.7
14/3/90	9	**0.6**	225	**25**	124	0.2	2.6
15/3/90	0	0.2	225	**20**	134	0.0	2.4
16/3/90	2	0.2	200	**23**	131	0.2	2.2
17/3/90	6	0.1	200	**25**	127	1.6	2.0
18/3/90	8	0.2	200	**21**	131	0.0	1.8
19/3/90	2	0.1	200	**22**	126	0.0	1.7
20/3/90	2	0.1	200	**20**	123	0.0	1.8
22/3/90	9	0.2	205	**20**	112	0.2	2.2
23/3/90	4	0.3	200	**27**	122	2.4	2.4
25/3/90	6	0.3	182	**20**	81	6.8	3.0
26/3/90	3	**0.5**	175	**23**	74	**53.0**	3.0
27/3/90	2	0.3	325	**23**	44	**32.2**	3.0
28/3/90	4	0.2	325	15	36	**68.6**	2.9
29/3/90	0	0.1	285	13	74	**26.6**	2.7

	STATION 2			H.I.A.W.S.			DHM
DATE	SILT PLUME WIDTH	AV. BREAKER HEIGHT	WAVE DIR'N	WIND SPEED	WIND DIR'N	RAIN to 0900	H.W. LEVEL
	m	m	deg	kn	deg	mm	m
2/4/90	0	0.1	215	13	95	**26.8**	1.9
3/4/90	0	0.1	235	2	45	**146.0**	2.0
4/4/90	0	0.1	247	12	80	**34.4**	2.3
5/4/90	0	0.1	225	2	60	**44.4**	2.4
16/4/90	0	0.0	275	3	5	**78.4**	1.8
17/4/90	0	0.1	245	8	103	**123.2**	1.8
18/4/90	0	0.0	202	12	73	**113.2**	1.9
19/4/90	0	0.1	245	14	48	**13.4**	2.0
11/5/90	**15**	0.1	241	12	101	0.4	2.3
23/5/90	0	0.2	290	12	300	**64.4**	2.6
28/5/90	8	0.2	280	11	158	**10.8**	2.2
8/6/90	6	0.2	242	**26**	142	**24.8**	2.2
9/6/90	4	0.2	195	**24**	145	0.2	2.2
10/6/90	4	0.3	230	**26**	144	0.2	2.2
11/6/90	0	0.2	220	**23**	137	0.0	2.1
15/6/90	**10**	0.1	200	18	133	0.0	2.1
16/6/90	**15**	0.1	235	18	174	**13.8**	2.2
17/6/90	2	0.2	295	2	270	**20.0**	2.4
18/6/90	**10**	0.1	210	6	178	0.2	2.6
19/6/90	**15**	0.2	215	19	161	0.0	2.8
20/6/90	5	**0.6**	205	**33**	134	0.0	3.0
21/6/90	6	**0.4**	230	**23**	141	3.0	2.3
24/6/90	**15**	0.1	310	2	70	8.6	2.3
7/7/90	0	0.3	215	**20**	141	0.0	2.2
27/7/90	**10**	0.0	270	3	270	0.2	2.2
30/7/90	0	0.2	230	13	195	**11.2**	2.1
31/7/90	**10**	0.0	240	7	238	0.4	2.2
2/8/90	0	0.1	225	15	170	**12.0**	1.9
7/8/90	0	0.3	230	**20**	178	0.0	2.4
9/8/90	**10**	0.1	260	2	273	0.0	2.5
15/8/90	**300**	0.3	300	**26**	312	0.0	2.5
17/8/90	0	0.2	225	**21**	178	0.0	2.1
18/8/90	0	0.2	230	**28**	163	0.0	2.2
28/8/90	**12**	0.2	240	15	133	0.0	2.0

DATE	STATION 2 SILT PLUME WIDTH m	AV. BREAKER HEIGHT m	WAVE DIR'N deg	H.I.A.W.S. WIND SPEED kn	WIND DIR'N deg	RAIN to 0900 mm	DHM H.W. LEVEL m
2/9/90	**10**	0.1	215	N/A	N/A	N/A	2.2
4/9/90	0	0.3	230	**22**	178	0.0	2.4
10/9/90	**10**	0.1	210	18	124	0.0	2.5
17/9/90	0	0.2	220	**20**	143	3.0	2.5
18/9/90	0	0.2	220	17	105	**11.8**	2.6
20/9/90	**10**	0.2	290	12	106	0.0	2.6
30/9/90	**15**	0.2	315	8	88	0.0	2.5
7/10/90	**15**	0.2	220	11	150	0.0	2.9
12/10/90	0	0.3	290	**21**	320	0.0	2.5
6/11/90	6	**0.5**	230	**23**	136	0.0	3.0
7/11/90	7	**0.5**	250	18	147	0.0	2.8
8/11/90	N/A	N/A	N/A	**20**	131	1.4	2.6
18/11/90	0	**0.8**	315	12	321	0.0	2.7
19/11/90	6	0.3	200	**25**	115	0.0	2.7
2/12/90	**12**	0.1	300	5	13	0.0	3.2
3/12/90	3	**0.4**	310	12	347	0.0	3.2
4/12/90	0	**0.5**	310	9	312	0.0	3.2
18/12/90	6	**0.8**	290	16	104	0.0	2.8
19/12/90	4	**0.7**	300	11	96	0.0	2.8
20/12/90	4	**0.7**	310	11	94	0.0	2.7
21/12/90	4	**0.5**	320	3	72	0.0	2.7
2/1/91	5	**0.4**	328	15	71	**13.6**	3.2
3/1/91	7	**0.6**	325	**20**	76	**13.6**	3.1
4/1/91	**10**	0.3	310	**20**	50	**73.6**	3.0
5/1/91	5	0.1	310	**22**	16	4.0	2.8
8/1/91	6	0.2	230	**20**	112	3.6	2.2
10/1/91	0	0.1	190	**23**	108	1.6	2.1
28/1/91	N/A	N/A	N/A	9	326	**13.4**	3.0
2/2/91	6	0.2	330	11	78	**12.2**	3.0
3/2/91	**80**	0.2	205	17	88	**21.2**	2.7
6/2/91	0	0.1	320	18	21	**10.4**	2.0
10/2/91	0	0.1	170	7	91	**31.4**	2.2

DATE	SILT PLUME WIDTH m	AV. BREAKER HEIGHT m	WAVE DIR'N deg	WIND SPEED kn	WIND DIR'N deg	RAIN to 0900 mm	H.W. LEVEL m
	STATION 2			H.I.A.W.S.			DHM
12/2/91	1	0.2	220	**20**	140	0.6	2.8
14/2/91	**15**	0.2	225	11	96	9.2	2.9
16/2/91	**20**	0.2	300	6	107	0.0	2.9
25/2/91	3	0.1	205	**21**	102	3.6	2.4
26/2/91	8	0.3	170	**22**	104	0.0	3.0
27/2/91	**10**	0.2	190	16	104	6.4	3.1
1/3/91	**20**	0.2	315	11	91	0.0	3.1
6/3/91	2	0.2	190	**21**	106	0.0	2.1
7/3/91	2	0.1	230	**29**	115	0.0	1.9
18/3/91	**10**	0.2	190	18	118	0.0	2.8
23/3/91	4	**0.4**	250	2	183	0.0	1.9
4/4/91	2	0.1	200	**20**	112	0.0	2.1
9/4/91	0	**0.4**	220	**22**	118	0.0	2.1
10/4/91	1	0.2	210	18	106	**20.6**	2.3
25/4/91	0	0.3	305	**20**	325	0.0	2.7
27/4/91	0	0.3	230	**20**	147	0.0	2.7

Appendix D

Specific Silt-producing Events

Event E3 (Figure 30), which occurred between 17 and 21 August 1989, produced the largest waves and most extensive silt plume recorded during the period that silt plumes have been observed, i.e. since April 1989. Winds were generally southeasterly, initially 20 kn for about 12 hours on 18 August, then after a brief lull rising to 30 kn early on 19 August and after a time dying away at an increasing rate to virtually nothing at midnight on 21 August. Day time high tides were about 2.7m but night time tides were higher, about 3.0m. Average breaking waves at station 2 on 19 and 20 August were 0.6 to 0.7m, while the maximum breaker height was estimated as 1.0 to 1.2m. Both these values are the maximum possible for the water depths on the reef flat during the day time high tide. Wave periods were 5 to 6s. Erosion of the beach face scarp at station 2, where consolidated silt deposits existed, was reported on 19 August. On both that day and the following day a large silt plume extended right across the reef flat south of the wreck. However there was no silt plume just before midday on 21 August when that day's observations were made, the average breaker height having fallen to 0.2m.

Wave action during event E3 was also strong at station 1 particularly on 19 August but no erosion scarp was observed. However "a mound of boulders" - coral rubble was observed at the run-up limit for the higher high tide on 20 August. Some rain occurred during the 48 hour period preceding the formation of the extensive silt plume on 19 August. There is no evidence to indicate whether this rain was a contributing factor to the development of the silt plume.

Events E2 (Figure 29) and E7 (Figure 34) during 25 to 29 July 1989 and 29 January to 1 February 1990 respectively represent two typical silt plume producing events about six months apart. In both cases the wind speed exceeded 20kn with wind directions southsoutheasterly to southeasterly on the first occasion and eastsoutheasterly during the second. Event E2 was somewhat more intense than Event E7. In both cases no rain was recorded. During the earlier period tides were quite small with day time high tides about 2.5m and night time high tides about 2.0m. Silt plume widths at station 2 during three days of this period were at least 15m with a maximum of 30m on 27 July 1989. Narrower plumes were observed at station 1. In contrast during the later period (Event E7) high tides were generally 2.6 to 2.8m. However the maximum silt plume width at station 2 was only 15m, plumes were only observed there on two days and no plumes were observed at station 1. However on both occasions the silt plume extended along the shoreline behind the boat harbour as far north as the northern line of concrete blocks on at least one day. During event E2 an erosion scarp was reported at both stations 1 and 2 and on 28 July when conditions were subsiding a build up of rubble together with more exposure of consolidated silt was noted at station 2. No erosion was recorded for event E7 and no scarp was present at station 1 during this event.

During both events E2 and E7 breaking wave heights were similar at stations 1 and 2. During the earlier period on 27 July the average breaker height observed was 0.5m which was almost the maximum possible with a tide height of 2.5m. At station 2 the wave period was 5.4s and waves were coming across the reef flat from the southwest, a direction consistent with ocean waves refracted across the reef rim after travelling up Wistari Channel. The recorded observations indicate that there was no significant breaking on the reef rim. On other days of both events, observed average breaker heights did not exceed 0.3m. During event E7 local wind generated wind waves of 1.5 to 2.0s were more visible but 4 to 5s waves were also present.

Events E2 and E7 illustrate the complexity of the situation. On the earlier occasion tides were low but waves were large and silt was available to be put into suspension. On the later occasion smaller waves at higher tides were able to remove silt from portions of the spoil dump not frequently exposed to wave action. The absence of rain may have meant that more fine material was present in the surface layers of the spoil dump than would have been the case after a wet period.

Events E5, E6 and E4 (Figures 32, 33 and 31) on 19 to 22, 27 to 30 November 1989 and 17 to 21 September 1989 respectively explain some of the apparent anomalies concerning the formation of silt plumes. In event E5, 25 to 30kn eastsoutheasterly winds at low high tides ($\leq$2.4m) caused only small waves breaking on the spoil dump beach. No silt plume was produced. Waves were observed breaking on the reef rim. Some rain was recorded on 20 November. In contrast during event E6 winds were less intense, 15 to 20kn, and more easterly. That is the spoil dump was well sheltered from them. Wave heights were small, 0.2m or lower, but day time high tides were higher at about 2.8m and a silt plume was observed.

In both events E5 and E6 the spoil dump was sheltered from the effects of the wind because it was blowing along the long axis of the reef and island. In the earlier case, the low tides caused ocean waves to break on the reef edge and no significant wave energy reached the spoil dump. Hence no silt plume occurred. In the later case, the tides were higher and, while the waves reaching the spoil dump were no higher than on the previous occasion, longer period waves (about 6s) were present. It is possible that these longer waves caused greater run-up which reached higher levels of the spoil dump where silty material had not been removed by previous wave action or recent rainfall. The width of the plume during event E6 may have been increased by offshore directed currents generated by the offshore wind. Observations record a silt plume form consistent with this action. It should also be noted that the observations on 28 November which give a silt plume width of 14m but a wave height of only 0.1m were made some time after high tide when the wave height may have been less than the one which produced the silt plume. Furthermore, it is always possible that unrecorded human activities such as regrading the beach face and removal of rubble disturbed the sediments on the spoil dump beach and caused the silt plume.

Event E4 two months earlier presents a different situation. Day time high tides were at least 2.8m, and average breaking wave heights were 0.5m. The scarp was eroded back underneath the jetty exposing more rubble and more consolidated silt. Tractor activity was noted at station 1. No rain was recorded. Despite all these favourable silt-producing conditions, the plume observed was narrow, only 2 to 4m wide. In this case the winds, while generally only 15kn but occasionally reaching 20kn, were northnorthwesterly. The spoil dump was directly exposed to the waves coming over the reef edge and relatively little reduction of wave height occurred because of refraction. The onshore winds generated onshore movement of water on the reef flat and so the silt plume was confined close to the shore, remaining essentially within the surf zone under all conditions.

The final two events E1, 25 May to 1 June 1989, and E8, 11 to 30 March 1990 show conditions near the beginning and the end of the current observation period. During event E1 (Figure 28) winds were between 20 and 30kn for about three days. Initially easterly on 27 May 1989, they become southeasterly after midday on 28 May. Tides were average in range with significant diurnal inequality. Day time tides were smaller than the night tides. A total of 85mm of rain was recorded on the three days, 26 to 28 May. Following the rain, average breaker heights at station 2 were 0.5m on 29 to 31 May. On 29 May it was noted that there were "monster waves breaking on [the reef] crest". The waves breaking on the beach were the maximum possible for the low high tide of 2.4m. An extensive very turbid silt plume up to 70m wide was produced by these conditions (Photo 11). This situation was aggravated by the reshaping of the beach face and erosion scarp by earthmoving equipment the previous day. The plume was extremely turbid under the jetty on 29 May due to the presence of silt disturbed during the previous day's operations., Conditions would probably have been worse during the higher night tide early on 29 May 1989.

Event E8 (Figure 35) extending from 11 to 30 March 1990 is the longest sustained windy event during the period of observation. Winds reached 30kn on 13 March and remained over 15kn for 15 days and over 20kn for half that period. Initially southeasterly to eastsoutheasterly, they gradually swung northwards to become easterly on 24 March and then northeasterly on 27 March. The latter part of the period was wet with heavy rain totalling 180mm recorded during the period 26 to 29 March. Tides varied from high spring tides just below 3.0m through neap tides with a high water of only 1.7m (range 0.4m) on 19 March and up to high spring tides $\geq$ 3.0m at the end of the period. Hence the known major potential silt-plume-generating factors all occurred during this event although their extreme values did not occur simultaneously. There is no record of significant human disturbance to the spoil dump during the duration of this event.

As the wind rose on 13 March, it was observed that the "whole reef [was] turbid and milky". The reasons for this are not clear (!) as the winds at the time of observation had only reached 20kn and the waves observed were not large. On the following day (14 March) after local winds had peaked at 30kn during the preceding night, the reef flat was not as milky, although the silt plume originating from the spoil dump in the vicinity of the jetty was somewhat more extensive than on the previous day. Waves coming from south of the reef were breaking on the reef edge along Wistari Channel and travelling across the reef flat. Wave heights were large, 0.6m at station 2, and were clearly being limited by the water depth over the reef flat in front of the spoil dump. Wave periods from 3 to 8s were present. Big rocks were moving on the beach. On 15 March the wind dropped, the waves were smaller and no silt plume was recorded. It appears that during this initial phase of event E8, the locally generated wind waves were sufficiently large on 13 March to stir up fine material on the reef flat and that this material was removed from, or dispersed over, the reef flat during the subsequent ebb tide. This process continued with the larger waves on 14 March, effectively cleaning the reef flat of available turbidity-generating material.

Between 17 and 22 March 1990, the winds were sustained generally above 20kn. Tides were low and hence observed breaking wave heights were low, although waves were observed breaking on the reef edge to the south virtually all the time but only occasionally on the northern reef edge. Waves of about 6s period were present most of the time. A silt plume was observed north of the jetty behind the boat harbour on 17 and 18 March. The waves observed on 18 March, particularly at station 1 were the largest possible in the very shallow water depth (0.8m) over the reef at high tide on this day. It is probable that they stirred up or eroded silt deposits on the reef flat between the spoil dump beach and the boat harbour. Subsequently on 19 to 21 March observed silt plumes were negligible.

As the high tide levels increased again after 21 March, wave heights increased to 0.3m and silt plumes reappeared. Plumes observed between 23 and 27 March were "streaky", that is, their seaward edge was not a smooth curve but was broken by one or more narrow tongues of turbid water extending seaward from the surf zone. The cause of this type of silt plume is not clear as its first occurrence on 23 March preceded a period of high high tides (3.0m) beginning 25 March, large waves (0.5m) on 26 March and a period of heavy rain between 26 and 29 March. It may have been associated with the shift in wind direction through easterly on 24 March to northeasterly on 27 March. From 25 March waves were breaking on the northern reef edge rather than the reef edge to the south. After 24 March the silt plume generally extended south from the jetty. On 26 March when 0.5m high waves of 5 to 6s period were approaching the spoil dump from the northwest, together with 2s waves from the southsoutheast, it was recorded that the "whole reef is cloudy". The silt plume was not particularly extensive although it was streaky. Again the cause of the cloudiness is not certain. However consideration of the observer's sketches of the silt plumes shows that the source of their turbidity was the spoil dump in the vicinity of the jetty and station 2. There is little evidence of silt being generated from other parts of the spoil dump. Cloudiness over the reef flat is, as previously suggested, likely to be caused by resuspension of sediments previously deposited there or possibly produced there.

During event E8, the silt plume width was always less than 10m, apart from streaks, and the rain near the end of the event did not have any observable influence upon the occurrence or size of the silt plumes.

Appendix E

Spoil Dump Sediment Samples

Summary

SPOIL DUMP SEDIMENT SAMPLES - SUMMARY

1 NATURAL BEACH SEDIMENTS

Sample Number	Location	Depth m	Analysis Process	d50 mm	Size Classification % clay	silt	sand	gravel
04489/2	SE above b/rock		S	0.900	0	0	97	3
04489/1	SE blowing sand		S	0.600	0	0	100	0
05489/8	SW above b/rock		S	1.150	0	0	91	9
30389/2	pump house	1.08	S	1.050	0	0	96	4
30389/3	pump house	2.89	S	0.980	0	1	87	12
30389/4	pump house	2.47	S	0.640	0	1	97	2
A1A(9/84)	Shark Bay upper		S	0.442	0	0	100	0
A1B(9/84)	Shark Bay upper	0.01	S	0.689	0	0	100	0
A2(9/84)	Shark Bay mid		S	1.271	0	0	98	2
A3(9/84)	Shark Bay lower		S	1.347	0	0	95	5
C/D1A(9/84)	E upper beach		S	0.307	0	0	100	0
C/D1B(9/84)	E upper beach	0.01	S	0.674	0	0	100	0
C/D2(9/84)	E lower beach		S	0.897	0	0	99	1
JY4(1/79)	NE swash deps		S	1.387	0	0	71	29
JY7(1/79)	NE behind shoal		S	0.547	0	0	100	0
E1(9/84)	NE upper beach		S	0.369	0	0	100	0
E2(9/84)	NE lower beach		S	0.647	0	0	99	1
E3(9/84)	NE sand shoal		S	0.683	0	0	100	0
JY6(1/79)	SW above HWM		S	0.536	0	0	100	0
JY5(1/79)	SW above b/rock		S	0.931	0	0	97	3
W1(5/88)	S above b/rock		S	0.750	0	0	100	0
W2(5/88)	S above W1		S	0.560	0	0	100	0
W3(5/88)	S below HWM		S	0.400	0	0	100	0
W4(5/88)	S above HWM		S	0.550	0	0	100	0
W5(5/88)	S upper beach		S	0.560	0	0	100	0
W6(5/88)	S upper(veg)		S	0.460	0	0	100	0
S1(9/84)	W (SD) upper		S	0.293	0	0	100	0
S2(9/84)	W (SD) upper		S	0.586	0	0	98	2
S3A(9/84)	W (SD) HWM		S	3.500	0	0	59	41
S3B(9/84)	W (SD) HWM	0.01	S	2.700	0	0	89	11
S3C(9/84)	W (SD) HWM	0.02	S	1.271	0	0	99	1
S4(9/84)	W (SD) base		S	1.200	0	0	96	4

Number of samples: 32

2 SPOIL DUMP

Sample Number	Location	Depth m	Analysis Process	d50 mm	Size Classification % clay	silt	sand	gravel
30389/1	AH 1	0.90	L	0.016	17	76	7	0
03489/1	A2	0.60	S	0.590	0	5	82	13
03489/3	A2	0.10	S/L	0.089	0	32	52	16
05489/2	B0	1.70	S/L	0.020	2	79	19	0
03489/2	B2	0.50	S/L	0.092	1	23	76	0
05489/5	B3	1.40	L	0.010	12	85	3	0
31389/4	C4	0.50	S	0.700	0	2	94	4
31389/1	C4	0.85	S/L	0.230	0	8	82	10
31389/3	C4	1.30	S/L	0.073	1	42	57	0
31389/2	C4	2.00	S/L	0.105	0	21	76	3
31389/5	C4	2.30	S	1.600	0	1	56	43
05489/6	D1	1.00	S/L	0.042	2	68	30	0
30389/6	NPWS core	?	L	0.023	4	84	12	0

Number of samples: 13

S = sieve analysis, L = laser analysis

SPOIL DUMP SEDIMENT SAMPLES - SUMMARY

3 SPOIL DUMP BEACH

Sample Number	Location	Depth m	Analysis Process	d50 mm	Size Classification % clay	silt	sand	gravel
05489/3	near A5		S	0.530	0	1	89	10
05489/4	rubble scarp		S/L	4.600	0	7	21	72
S1(5/88)	near A5		S	0.710	0	1	73	26
S2(5/88)	above rubble		S	3.350	0	0	51	49
S3(5/88)	between rubble		S	0.480	0	0	98	2
S4(5/88)	below rubble		S	1.720	0	0	57	43
S5(5/88)	lower beach		S	>4	0	0	32	68
S6(5/88)	beach step		S	3.930	0	1	49	50
S6A(5/88)	beach step	0.01	S	3.750	0	1	51	48
S7(5/88)	moat edge		S	0.750	0	1	97	2

Number of samples: 10

4 SILT PLUME

Sample Number	Location	Depth m	Analysis Process	d50 mm	Size Classification % clay	silt	sand	gravel
05489/1	off SD beach		L	0.013	8	88	4	0
J1(5/89)			L	0.017	4	85	11	0
J2(6/89)			L	0.027	0	81	19	0
J3(7/89)			L	0.030	0	88	12	0

Number of samples: 4

5 MOAT AND REEF FLAT, SOUTH OF JETTY

Sample Number	Location	Depth m	Analysis Process	d50 mm	Size Classification % clay	silt	sand	gravel
05489/7	on beach rock		S/L	0.270	0	9	74	17
06489/1	moat		S/L	0.690	0	6	88	6
04489/8	near pile 8		S/L	0.065	1	43	54	2
P1(12/89)	SE SD base		S	0.950	0	1	90	9
P2(12/89)	then extending		S	1.290	0	1	82	17
P3(12/89)	out across moat		S	0.750	0	1	98	1
P4(12/89)	from spoil dump		S	0.730	0	1	96	3
P5(12/89)			S	0.660	0	1	97	2
P6(12/89)			S	0.760	0	0	96	4
P7(12/89)			S	0.840	0	0	95	5
P8(12/89)			S	0.620	0	1	98	1
P9(12/89)			S	0.660	0	1	94	5
P10(12/89)			S	0.610	0	1	97	2
Q1(12/89)	near pile 8		S	0.104	0	8	92	0
Q2(12/89)	then extending		S	0.360	0	7	93	0
Q3(12/89)	out from spoil		S	0.650	0	2	95	3
Q4(12/89)	dump parallel		S	0.320	0	5	89	6
Q5(12/89)	to jetty		S	0.530	0	2	96	2
Q6(12/89)			S	0.380	0	4	95	1
Q7(12/89)			S	0.540	0	3	96	1
Q8(12/89)			S	0.660	0	0	80	20
Q9(12/89)			S	0.620	0	0	95	5
Q10(12/89)			S	0.620	0	1	98	1

Number of samples: 23

S = sieve analysis, L = laser analysis

SPOIL DUMP SEDIMENT SAMPLES - SUMMARY

6 BEACH AND FLAT BEHIND BOAT HARBOUR, NORTH OF JETTY

Sample Number	Location	Depth m	Analysis Process	d50 mm	Size Classification % clay	silt	sand	gravel
04489/3	near pile 7		S/L	0.430	0	33	46	21
04489/7	near pile 7		L	0.045	5	62	33	0
04489/5	below helipad		S	1.300	0	2	78	21
04489/4	below helipad		S/L	0.610	0	5	72	23
R1(12/89)	beach below wall		S	0.670	0	0	98	2
R2(12/89)	then extending		S	0.690	0	2	83	15
R3(12/89)	along line of		S	0.690	0	1	79	20
R4(12/89)	harbour leads		S	0.600	0	0	98	2
R5(12/89)	near fuel post		S	0.124	0	20	76	4

Number of samples: 9

7 BOAT HARBOUR

Sample Number	Location	Depth m	Analysis Process	d50 mm	Size Classification % clay	silt	sand	gravel
04489/6	centre basin		S/L	0.280	0	10	87	3
JY3(7/79)	spit swing basin		S	1.013	0	0	91	9
JY2(7/79)	in boat channel		S	1.193	0	0	84	16
JY8(7/79)	near breach		S	1.238	0	0	92	8
Ha1(12/89)	centre basin		S	0.230	0	11	88	1
Ha2(12/89)	NW jetty		S	0.710	0	4	91	5
Ha3(12/89)	then extending		S	0.122	0	21	79	0
Ha4(12/89)	along line of		S	0.300	0	7	93	0
Ha5(12/89)	harbour leads		S	0.091	0	24	76	0
Ha6(12/89)	NW "Protector"		S	0.370	0	2	98	0
Ha7(12/89)	near entrance		S	0.300	0	0	99	1

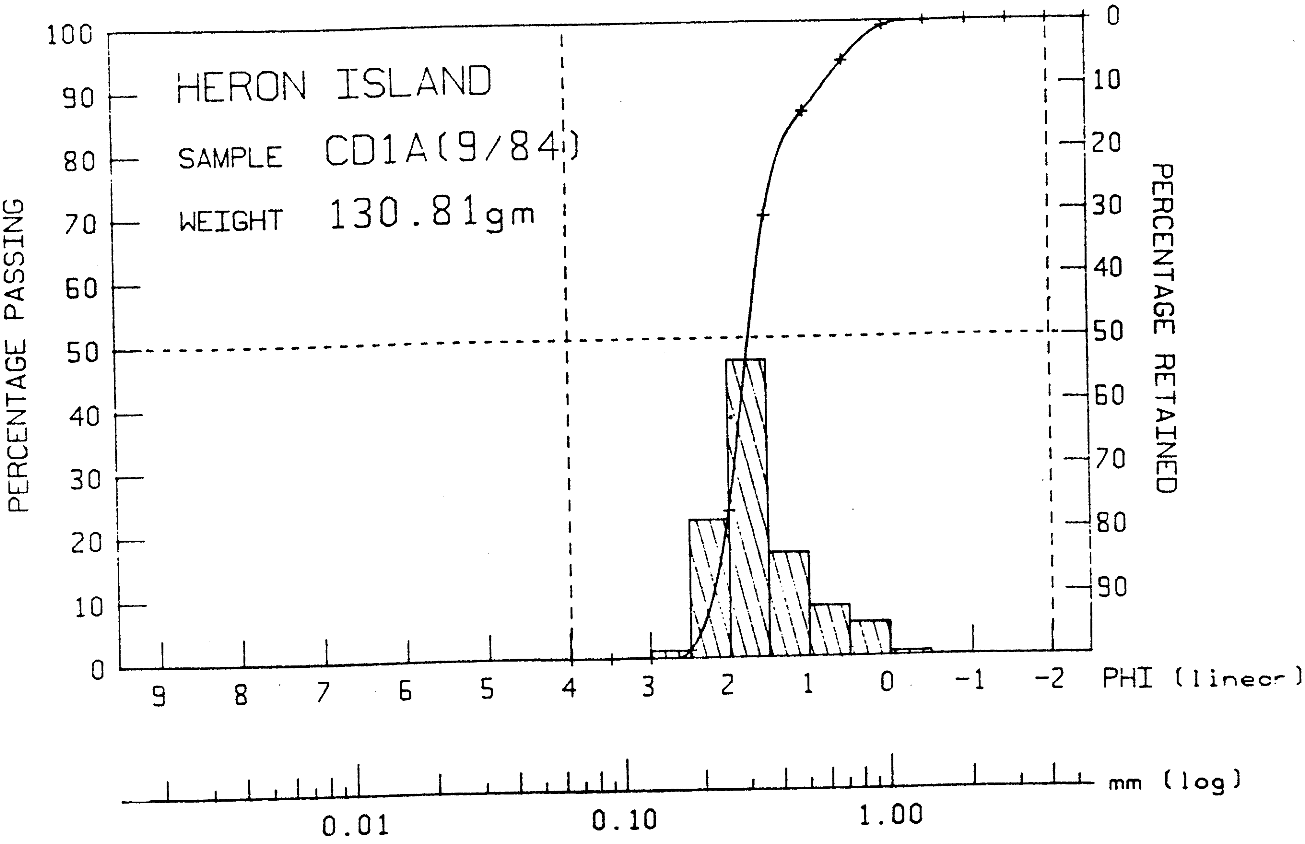
Number of samples: 11

Total number of samples: 102

S = sieve analysis, L = laser analysis

Appendix F

Grain Size Distribution Curves



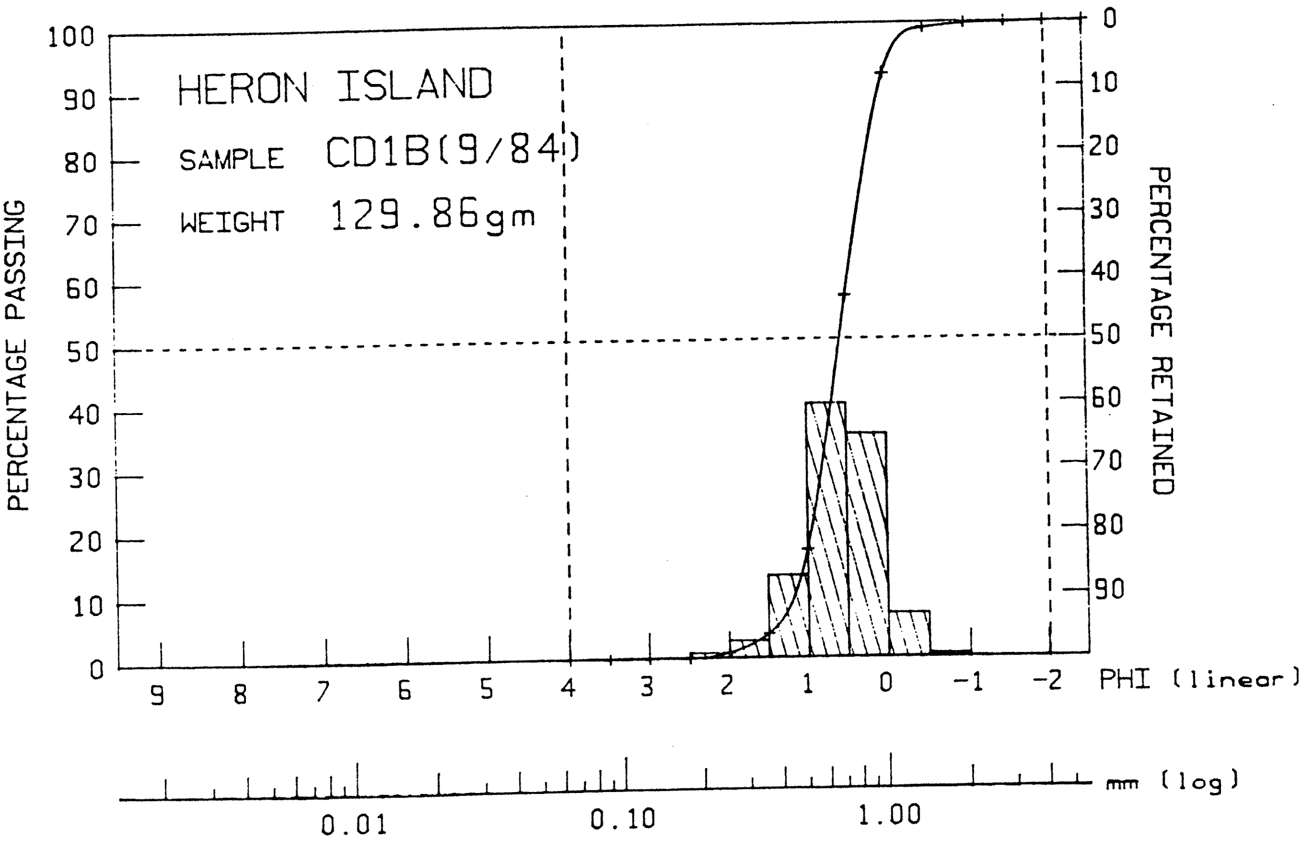
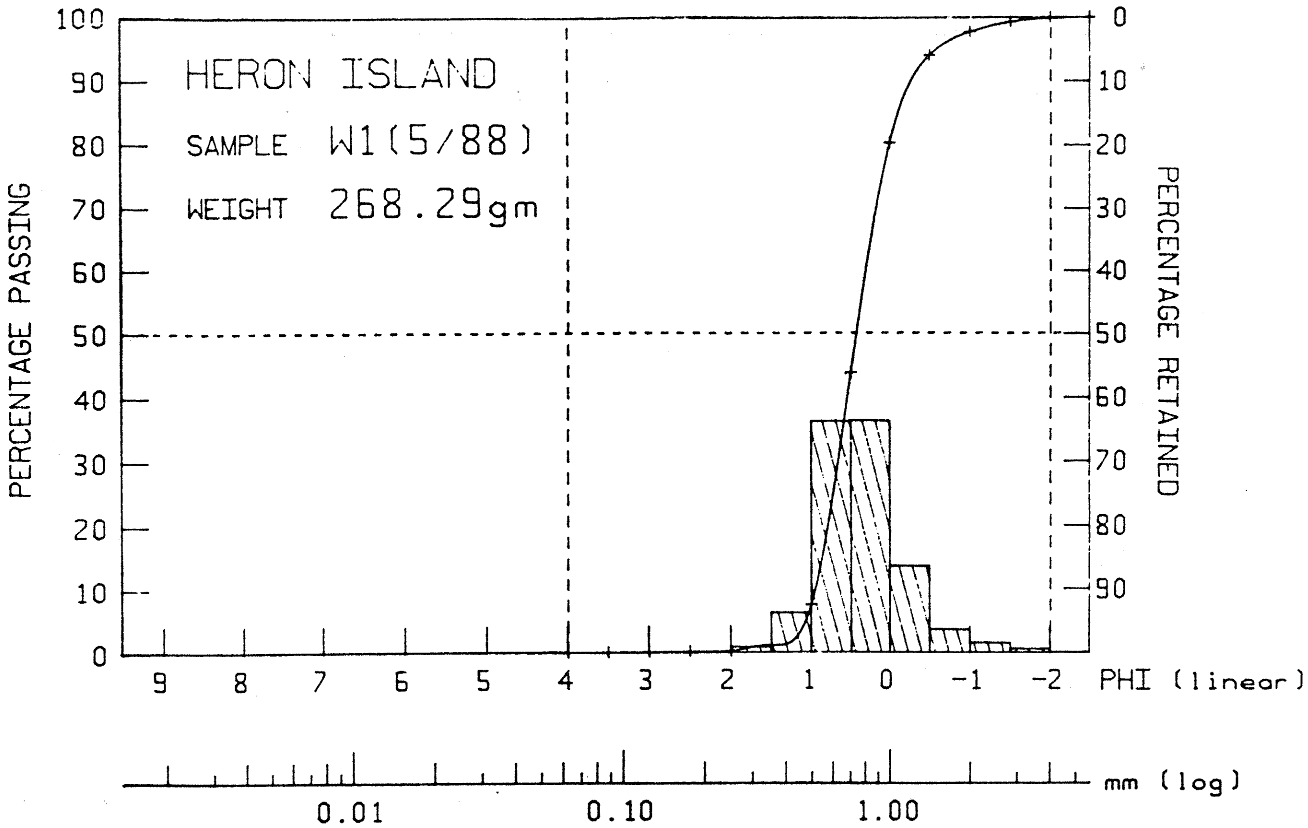


Figure F1. Beach at eastern end of island



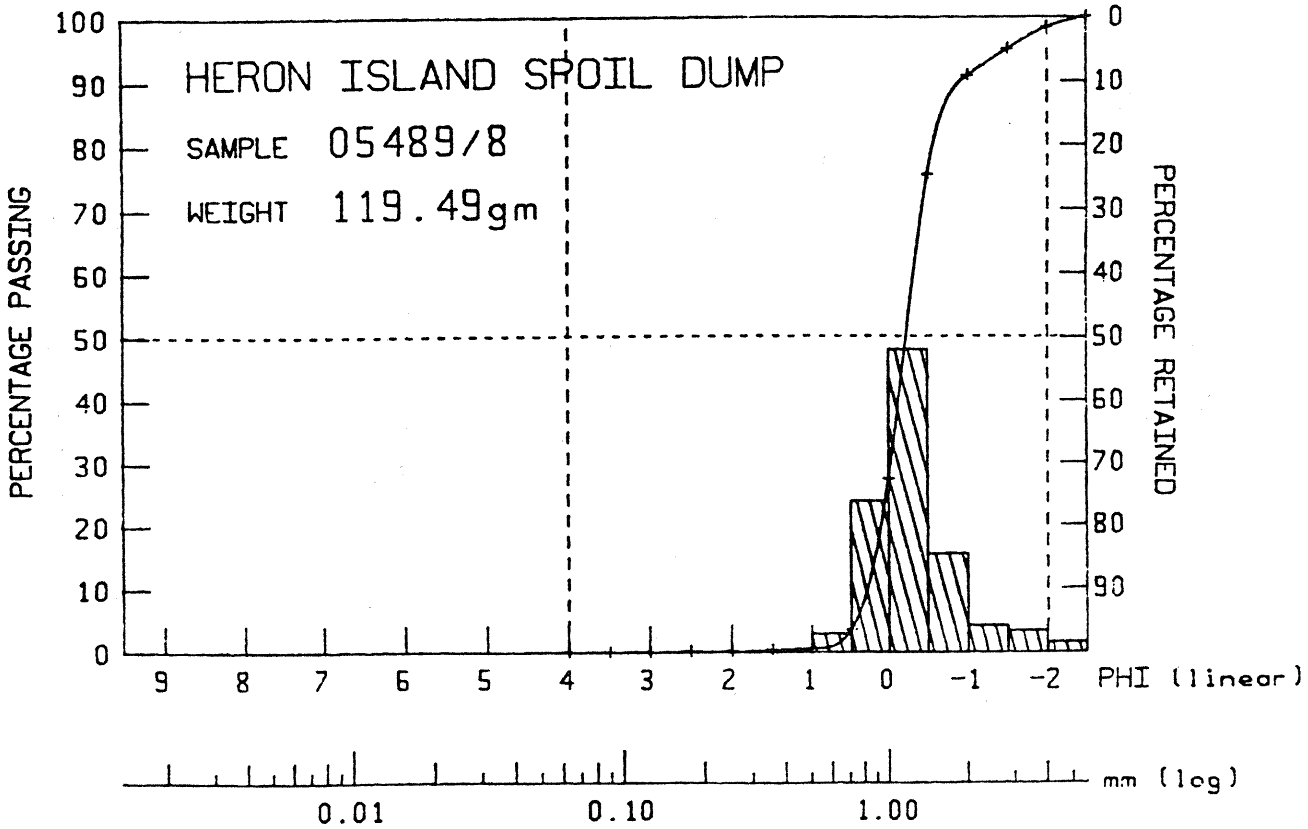
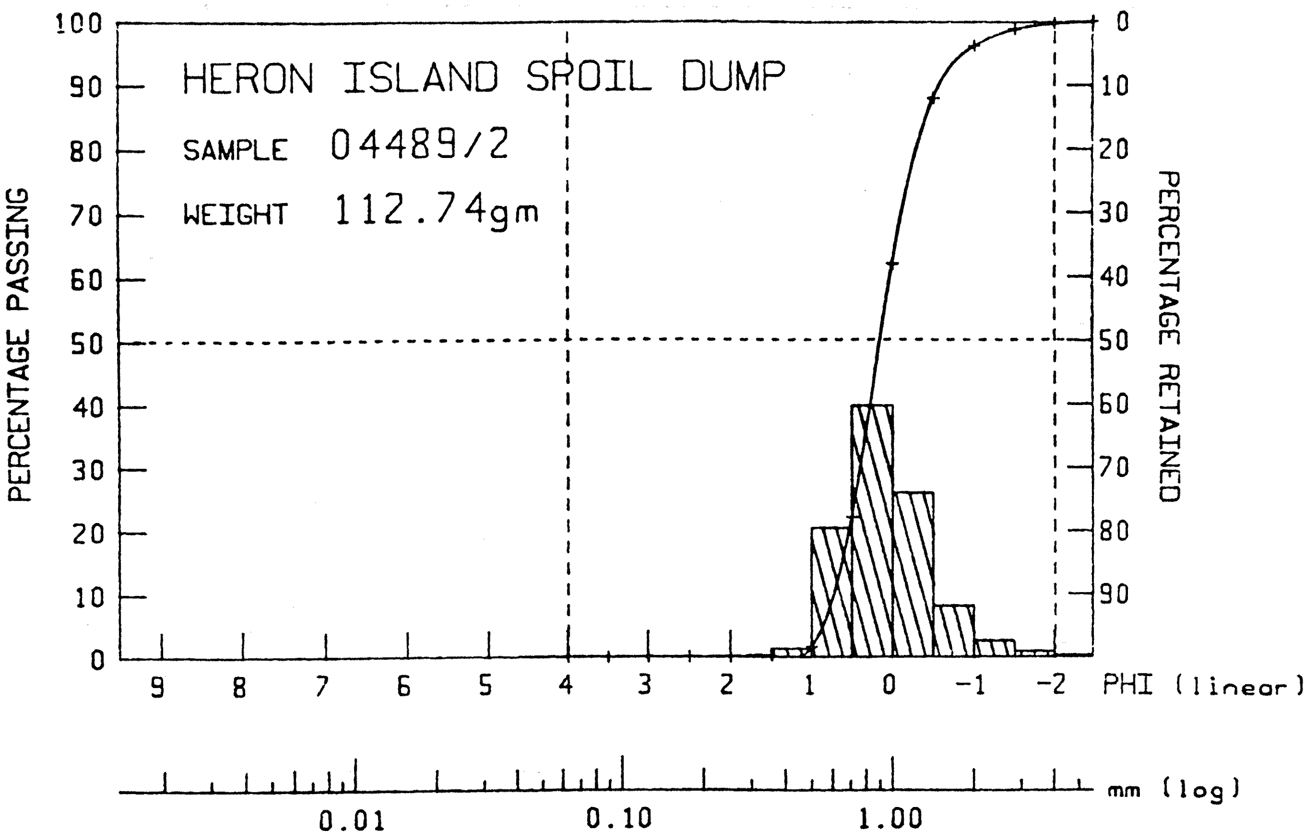


Figure F2. Beach above western end of beach rock



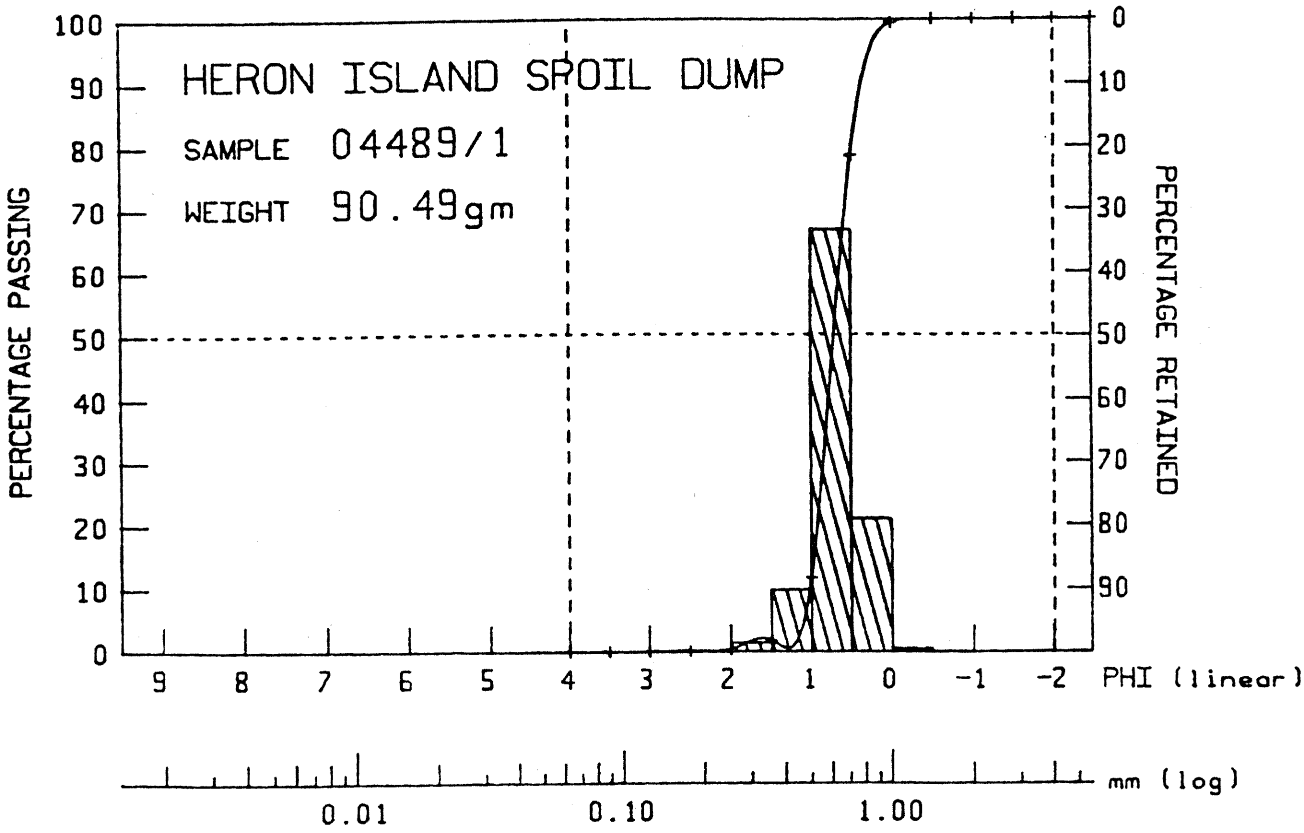
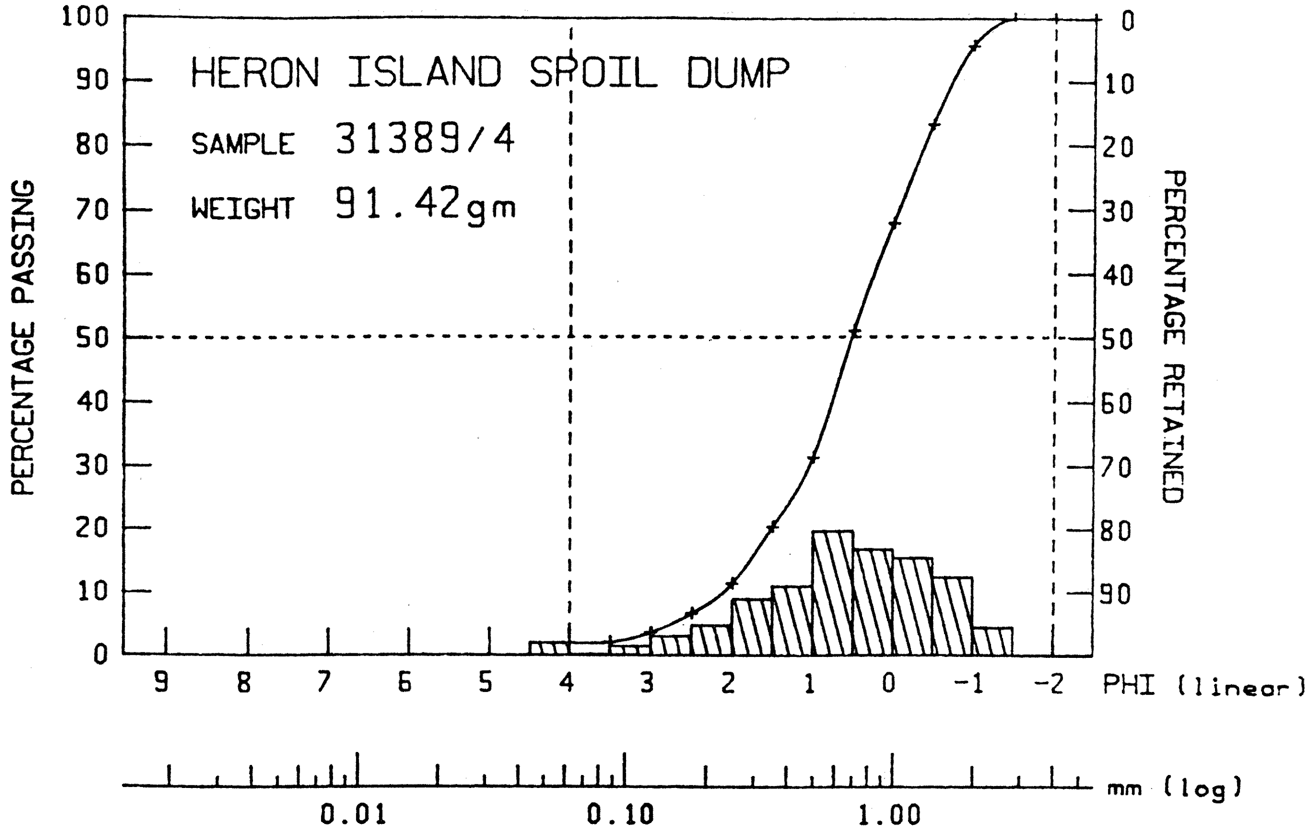


Figure F3. Beach above eastern end of beach rock



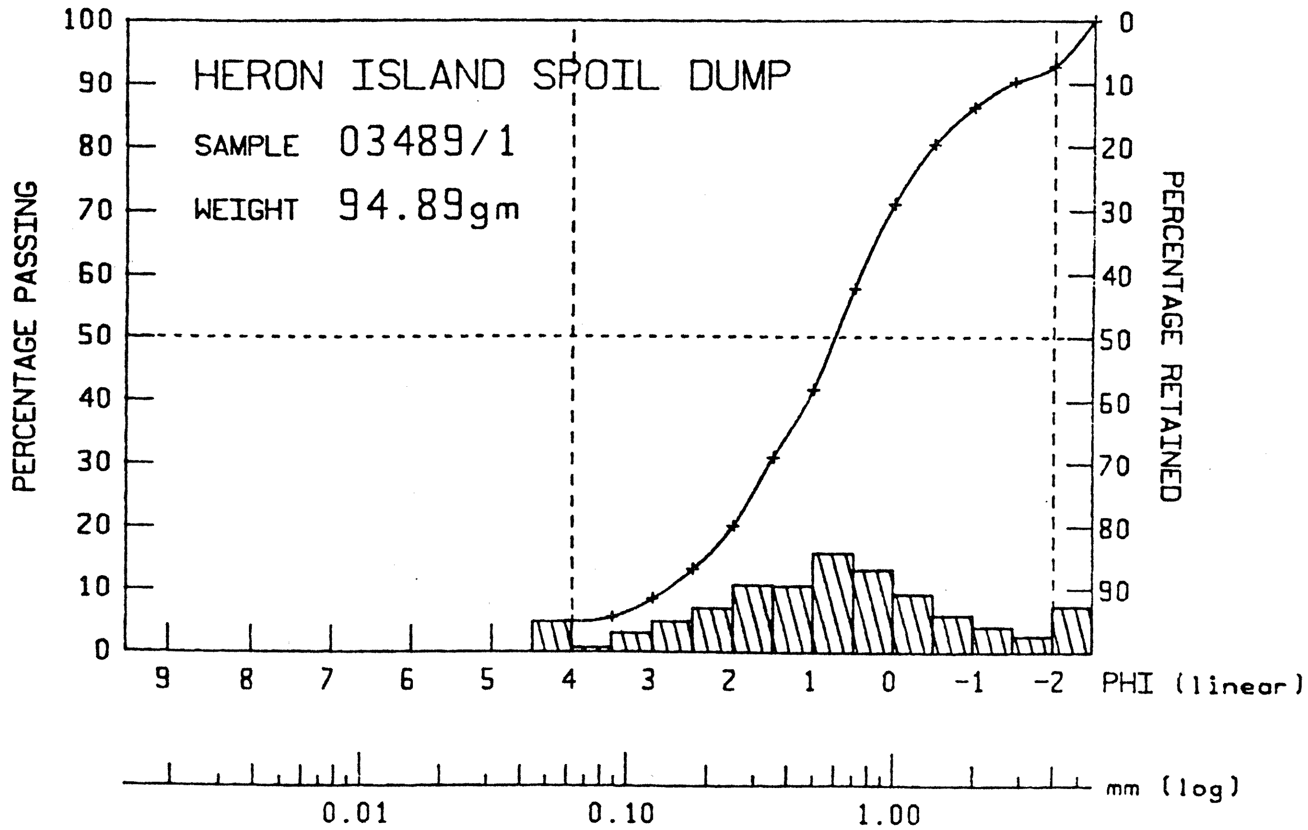
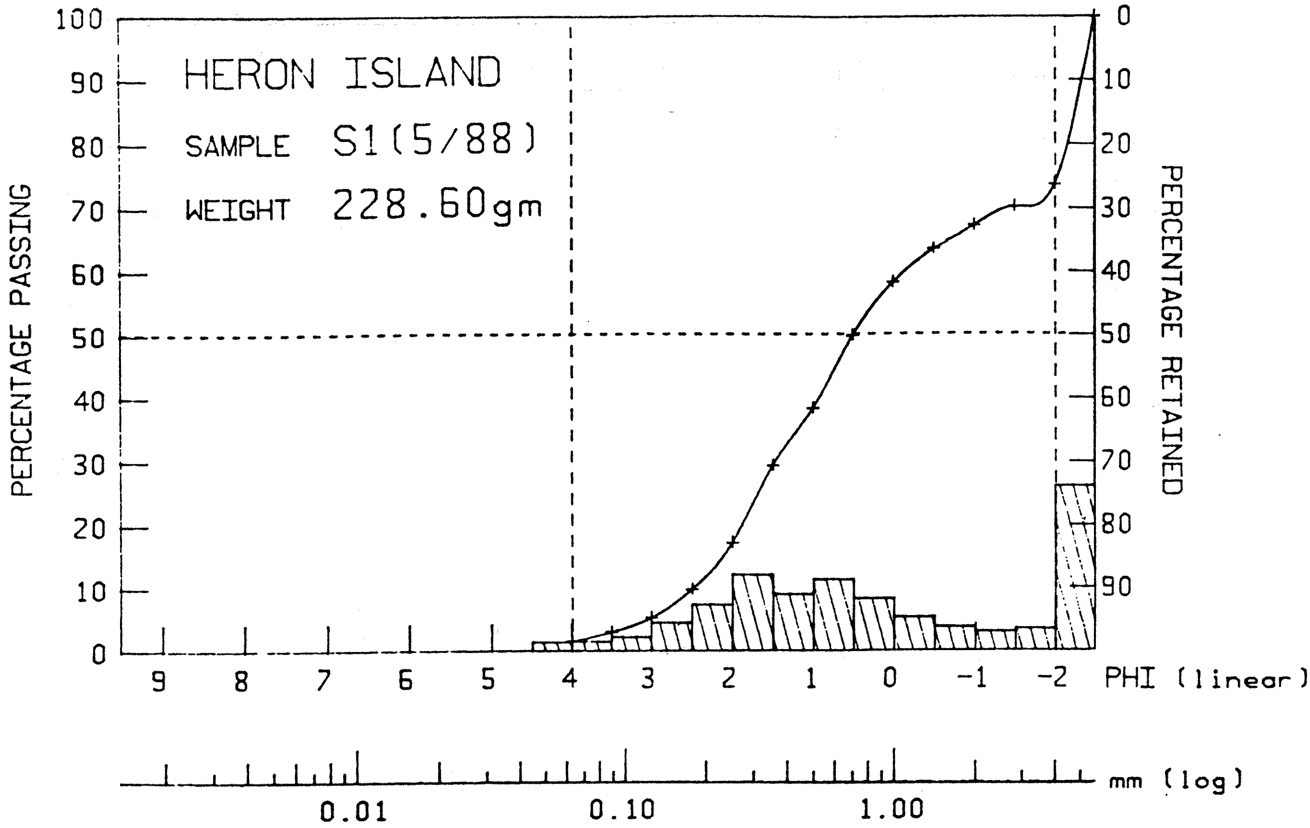


Figure F4. Spoil dump - holes A2 and C4



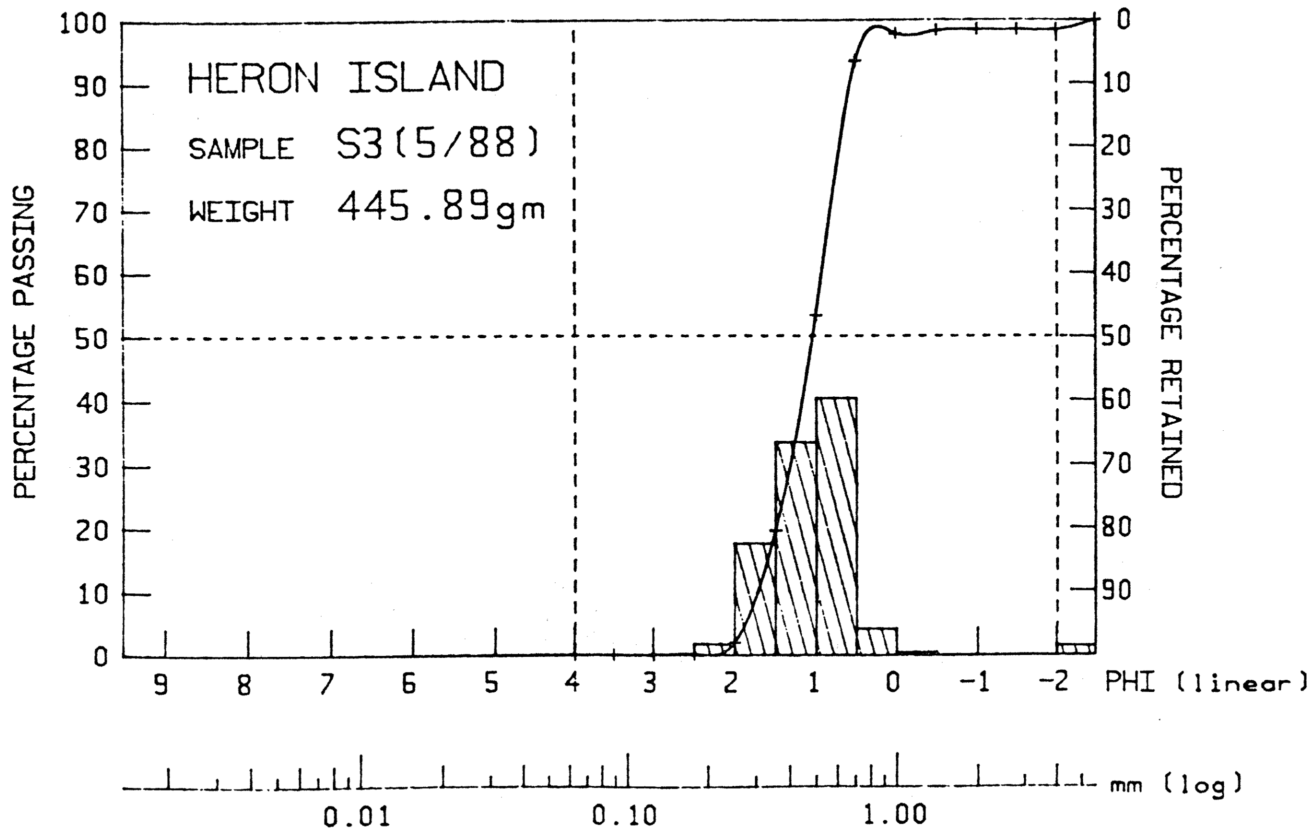
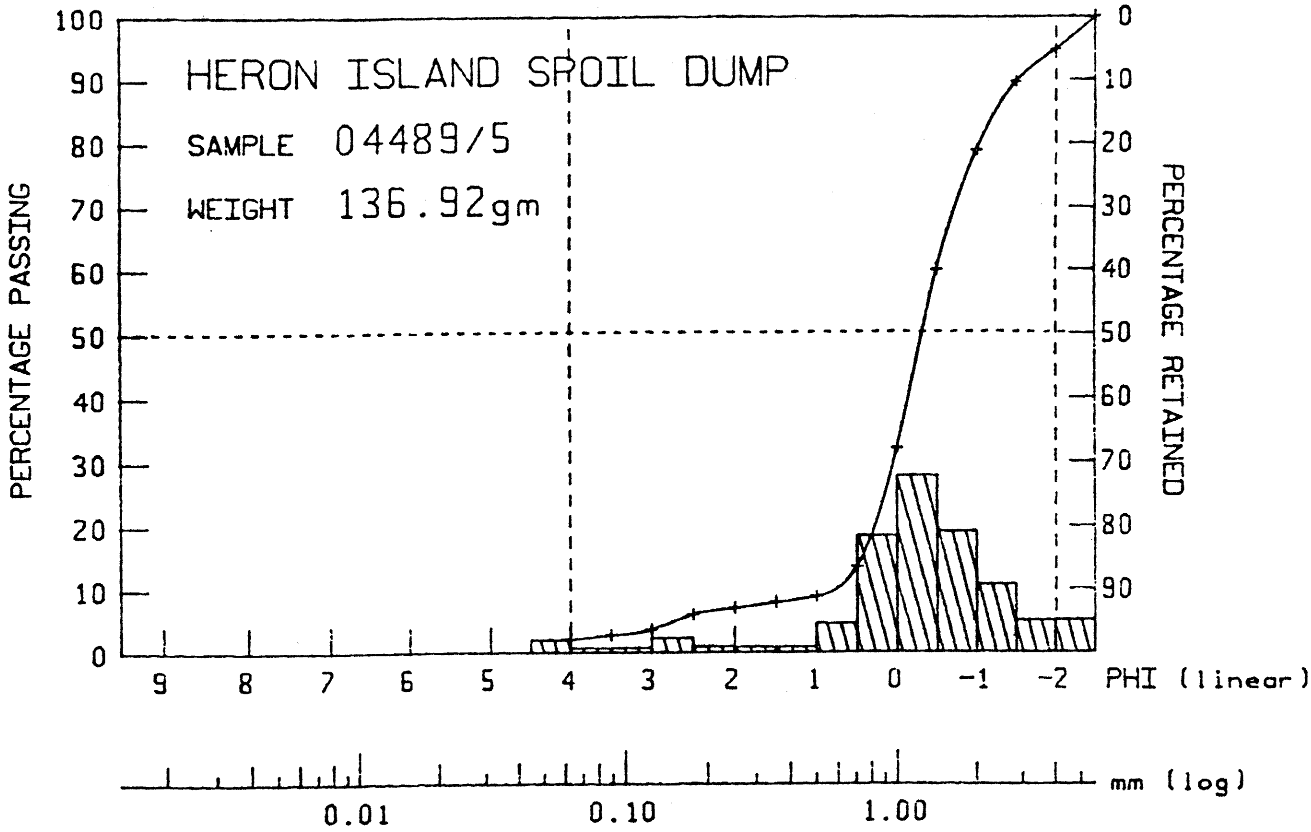


Figure F5. Spoil dump beach



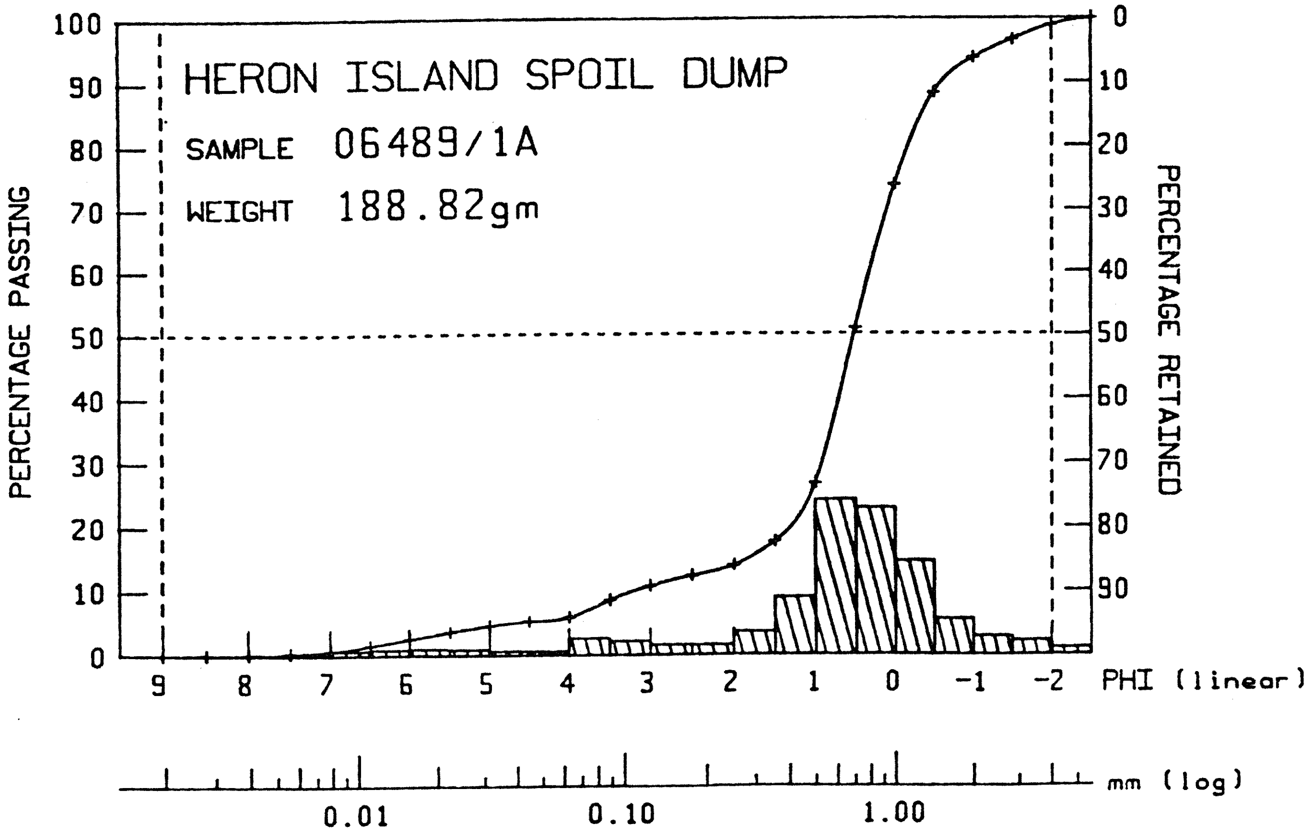
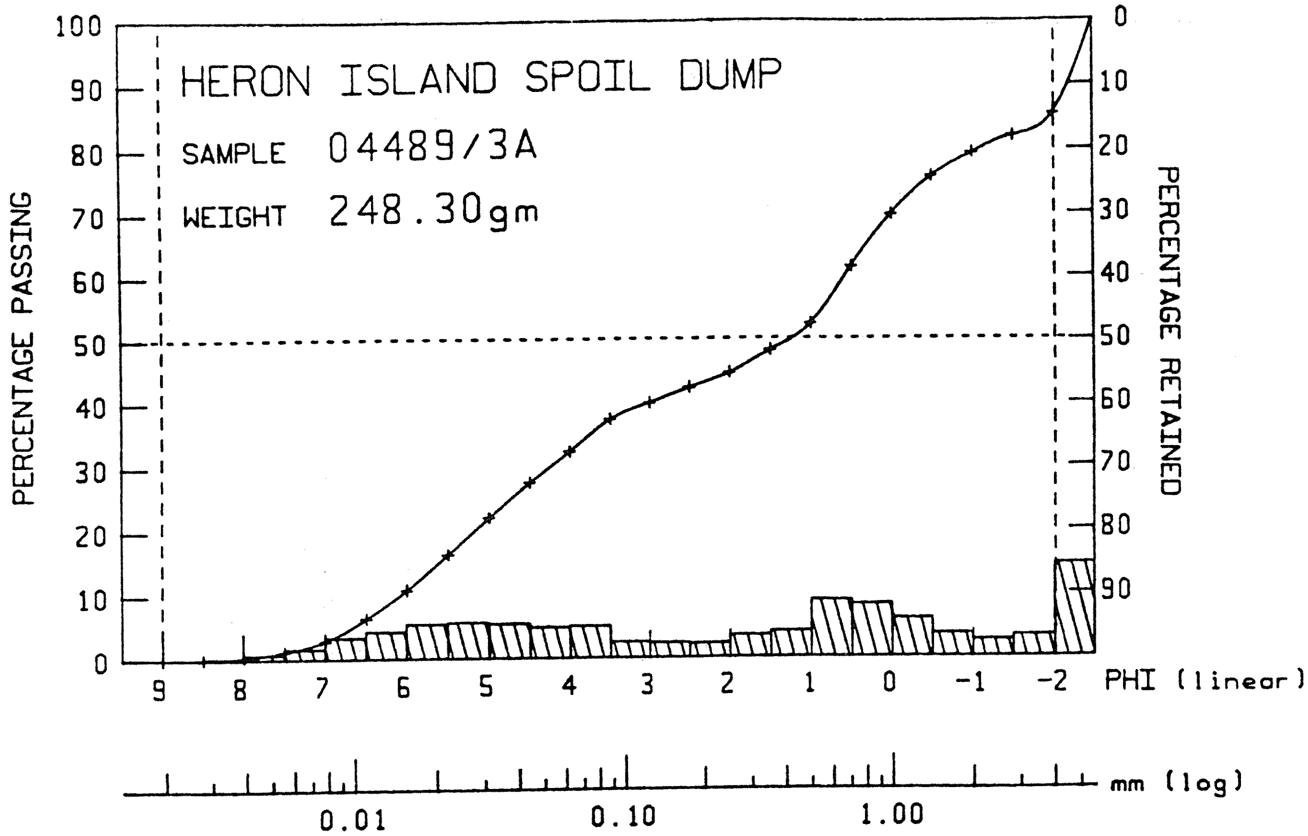


Figure F6. Boat harbour beach and moat adjoining spoil dump



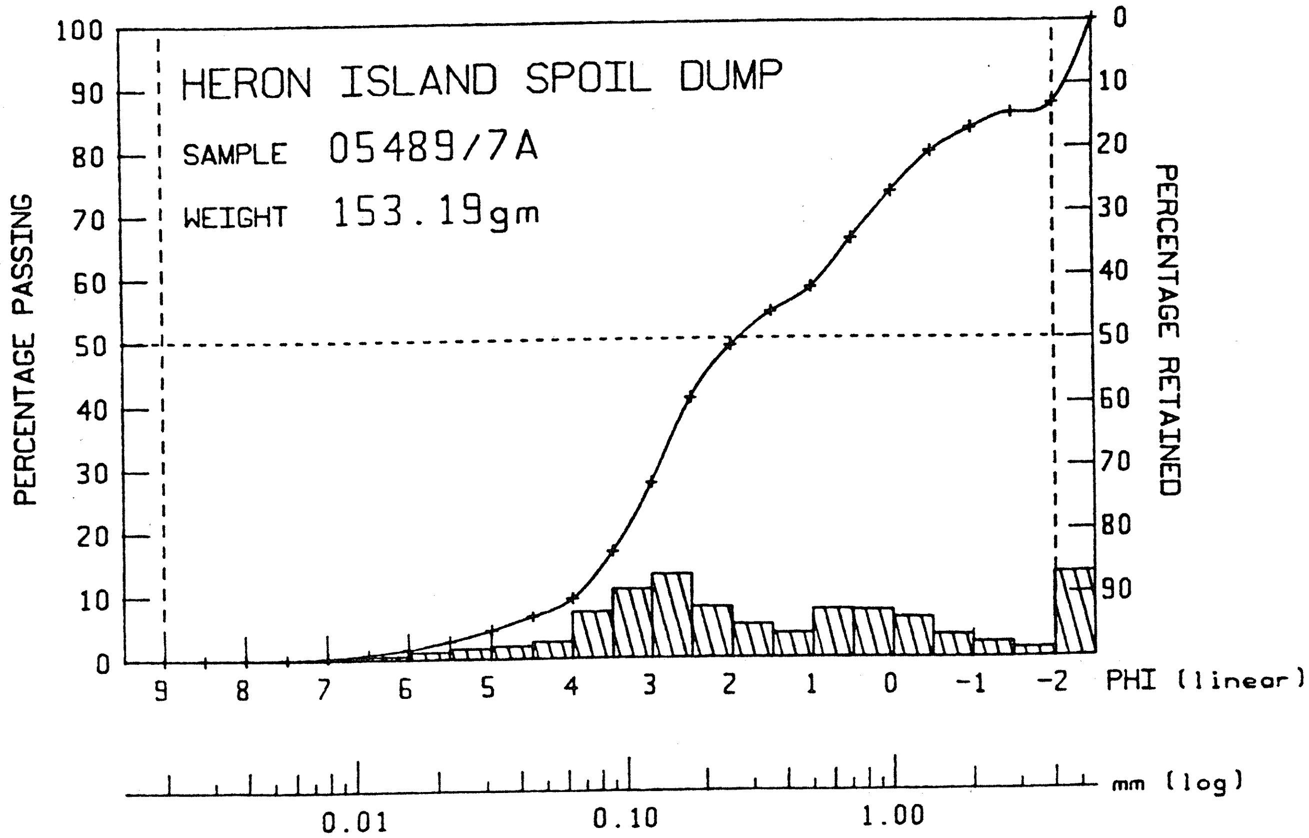
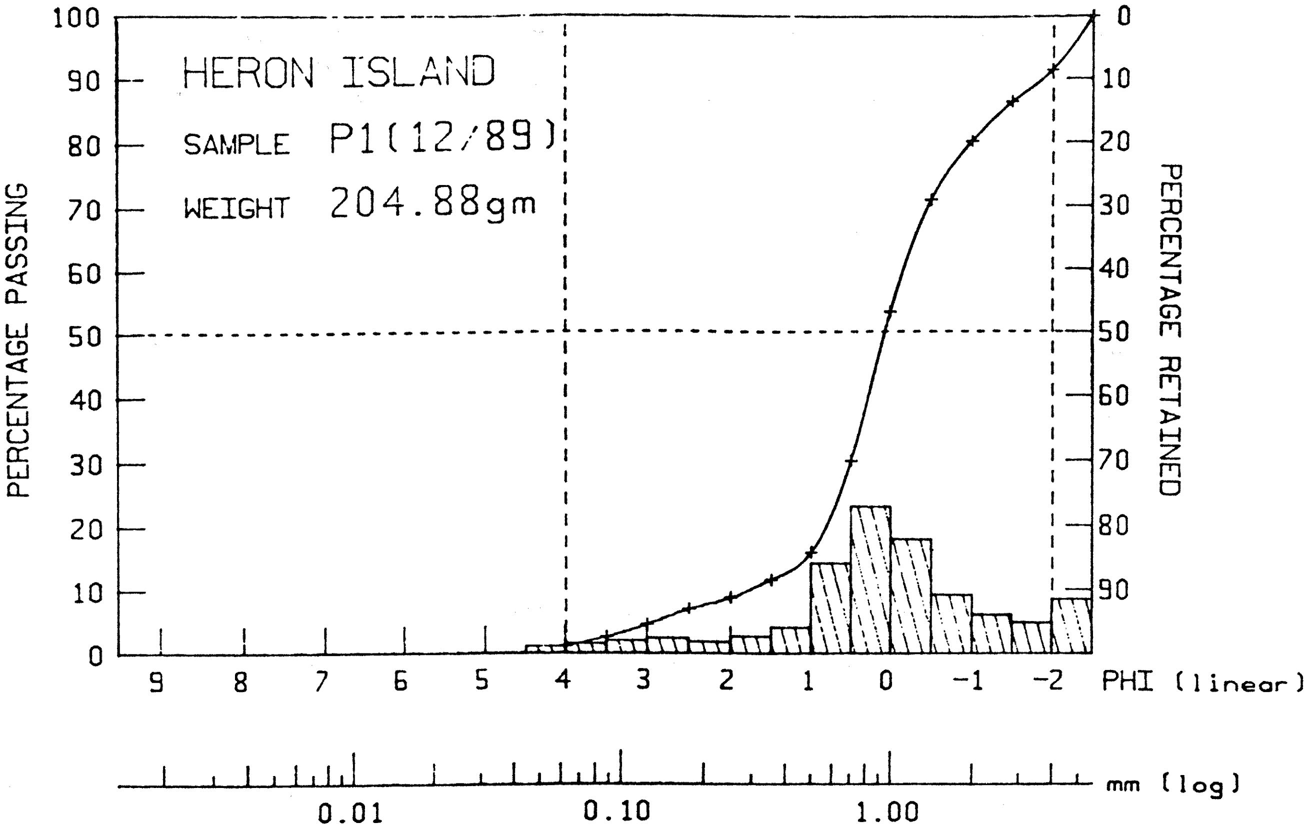


Figure F7. Reef flat behind boat harbour and lower part of western end of beach rock



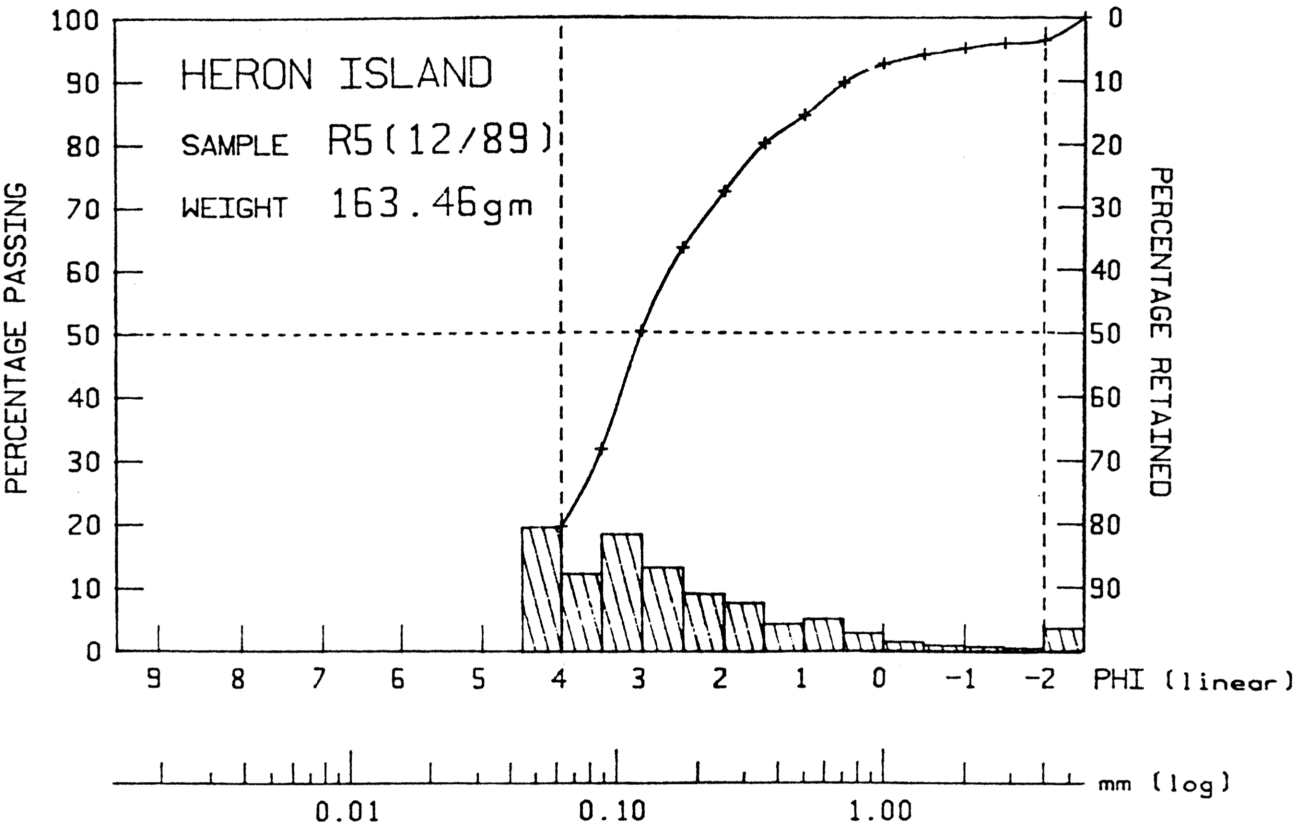
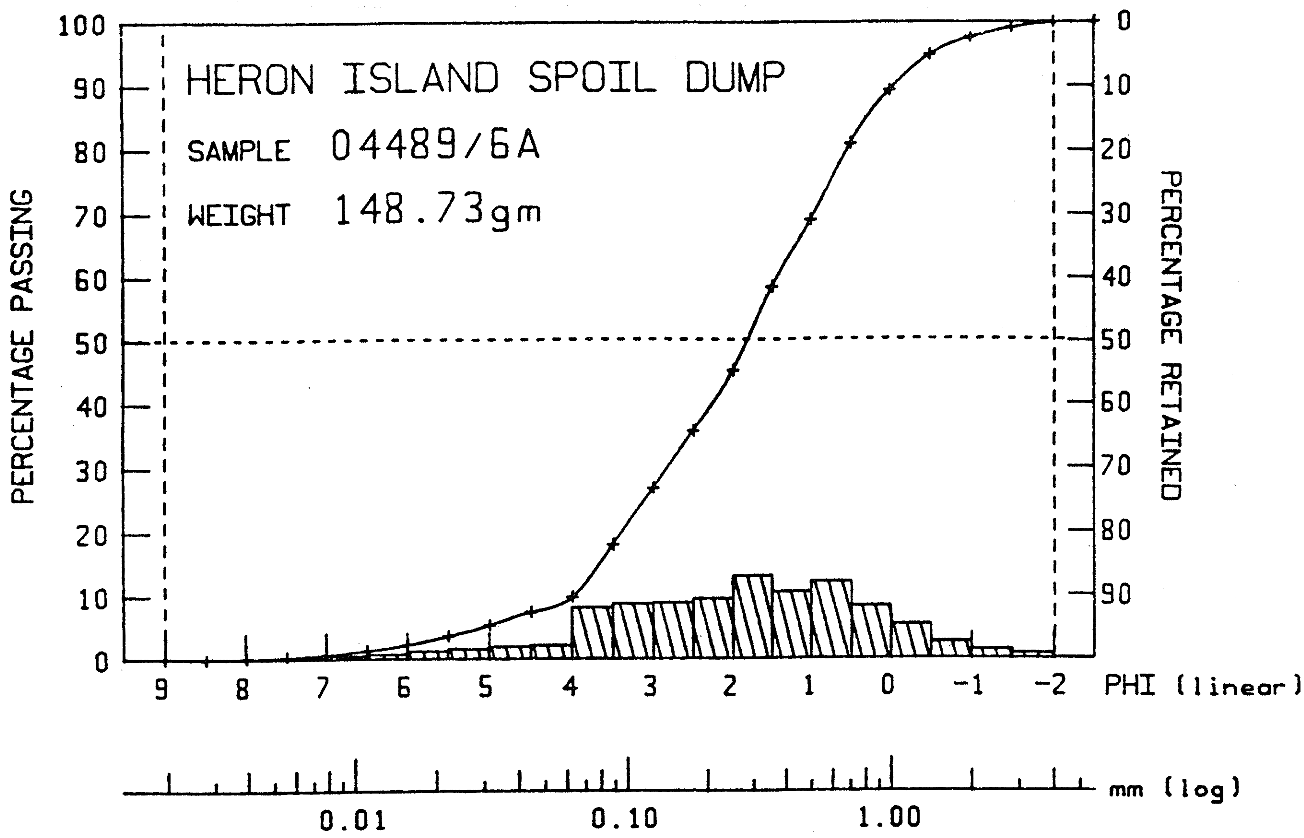


Figure F8. Reef flat in front of spoil dump



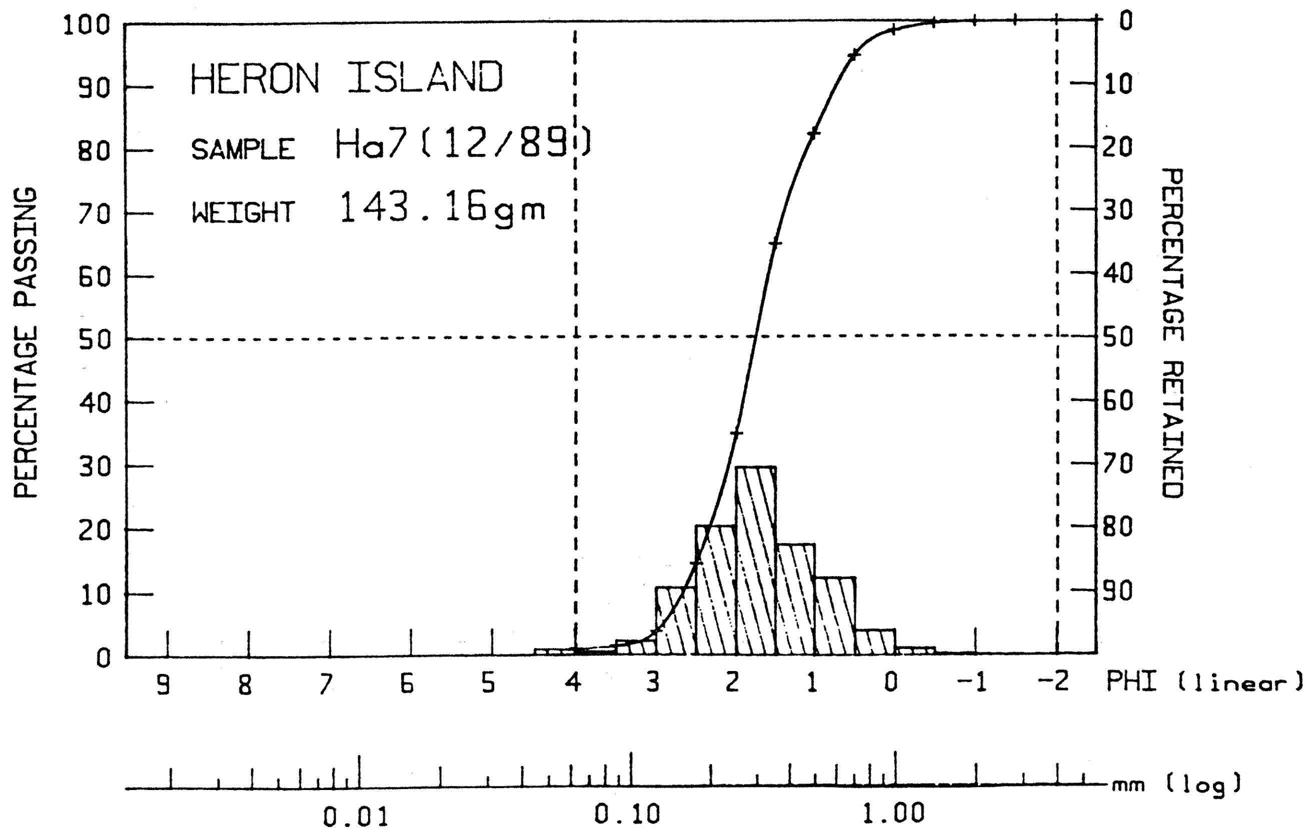
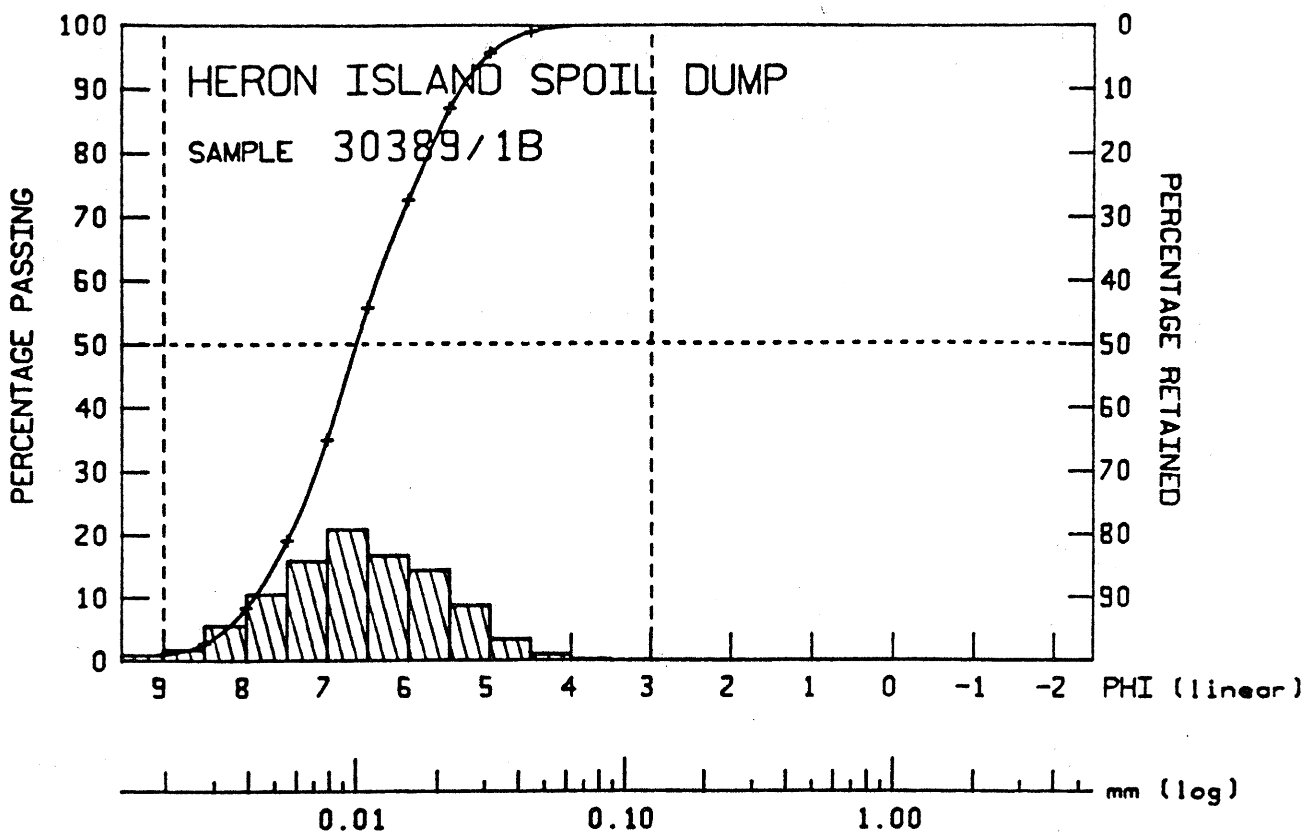


Figure F9. Bottom of boat harbour



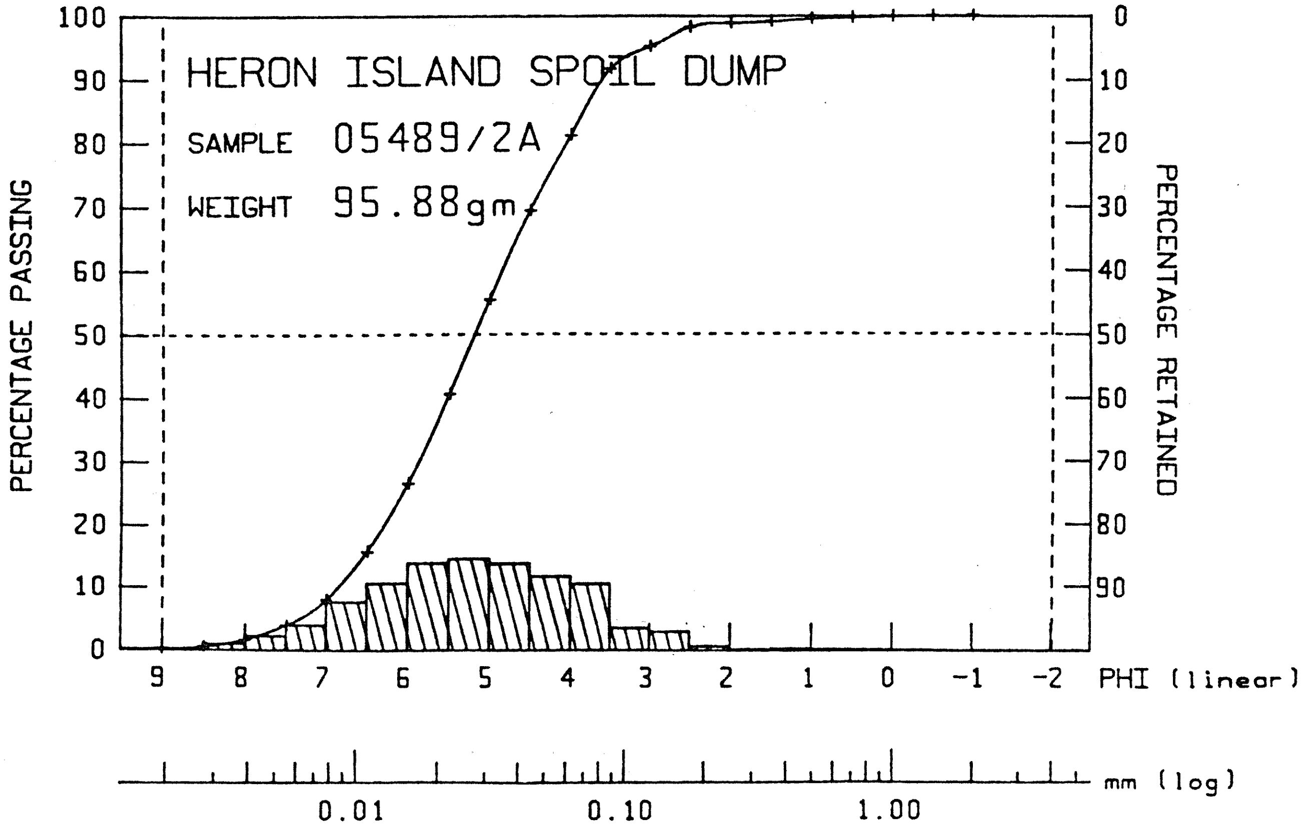
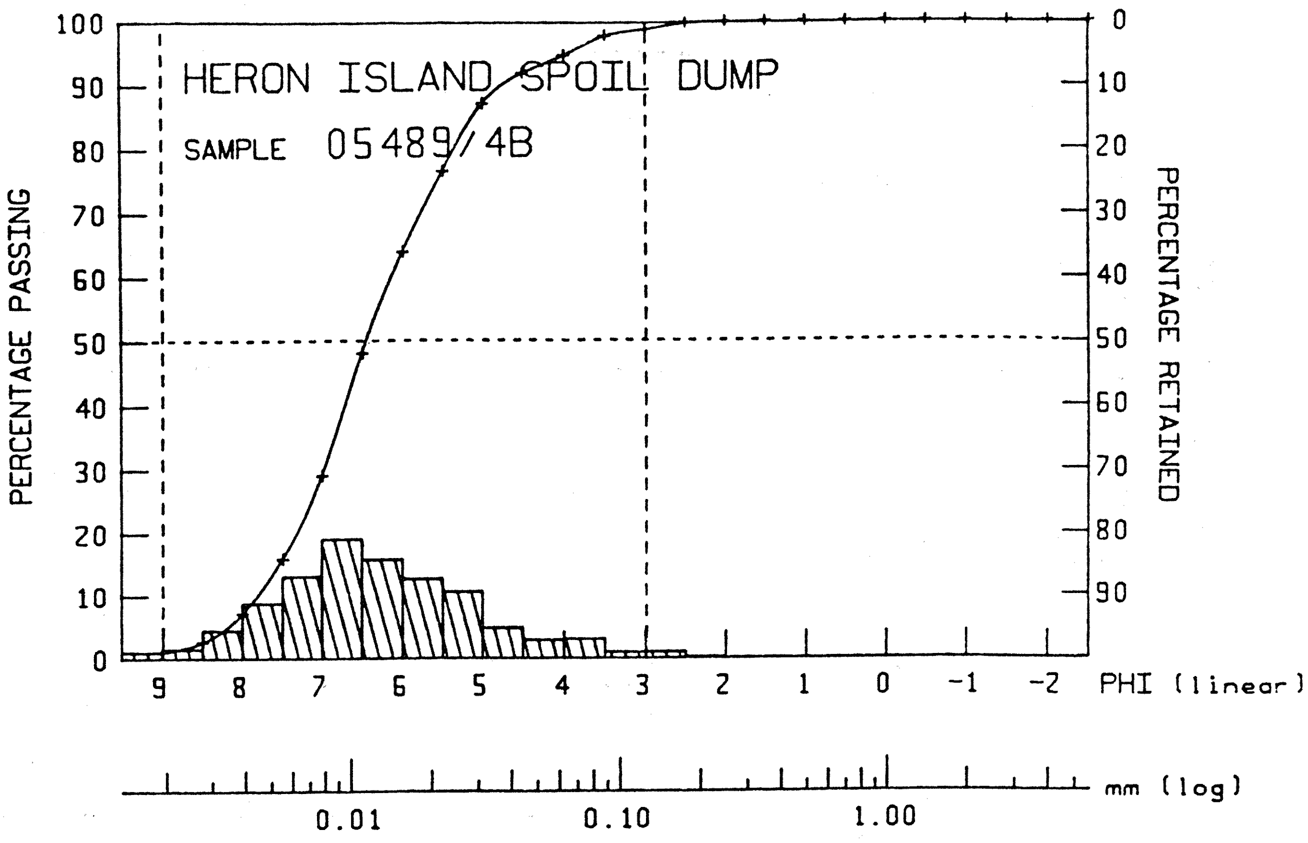


Figure F10. Silt from spoil dump



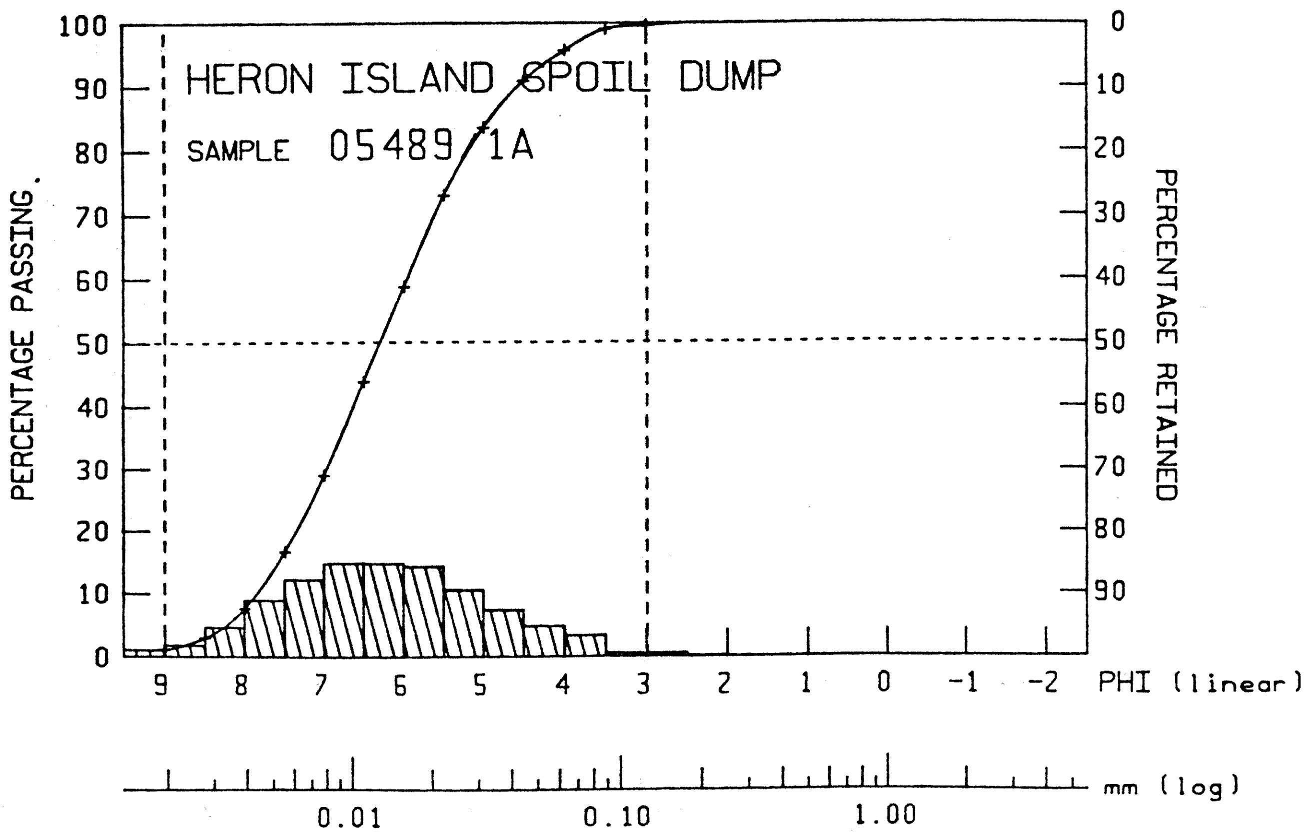
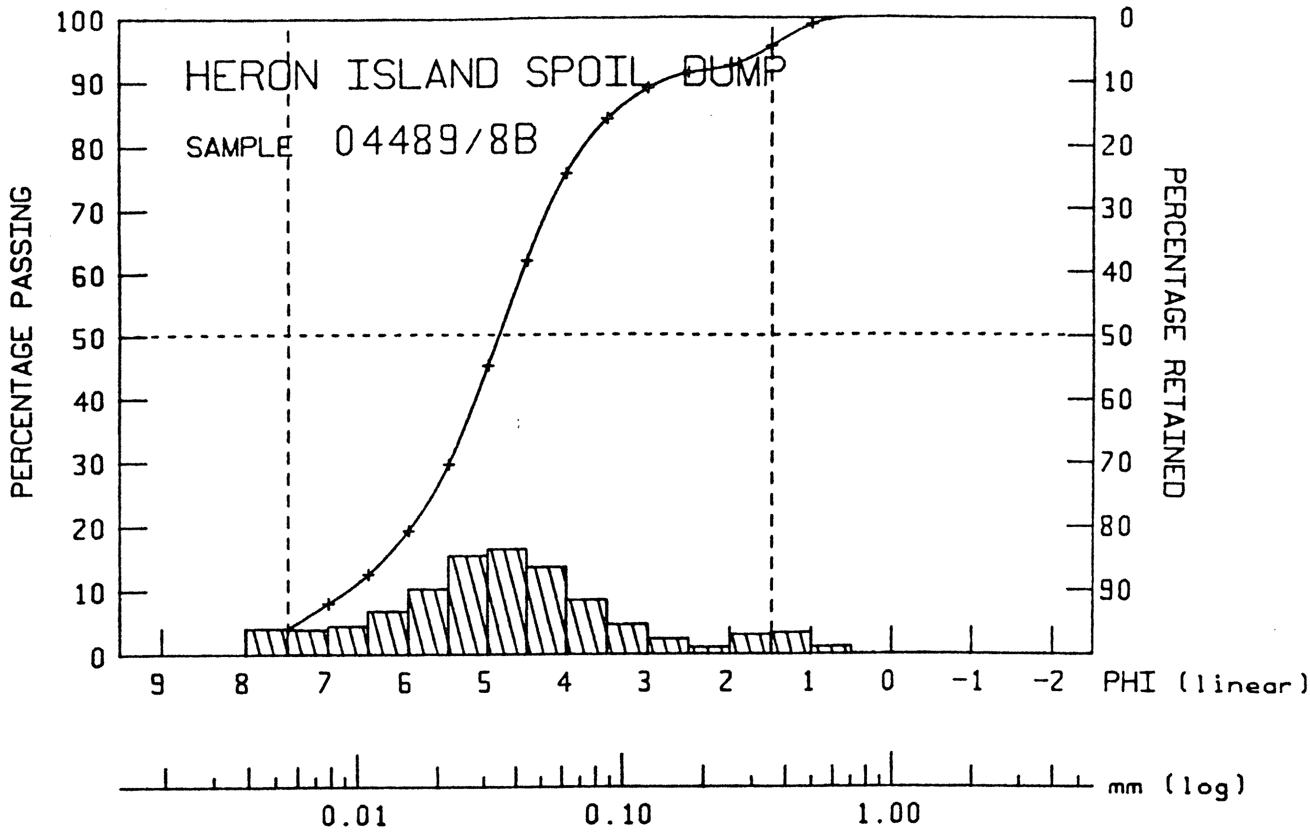


Figure F11. Silt from scarp and plume



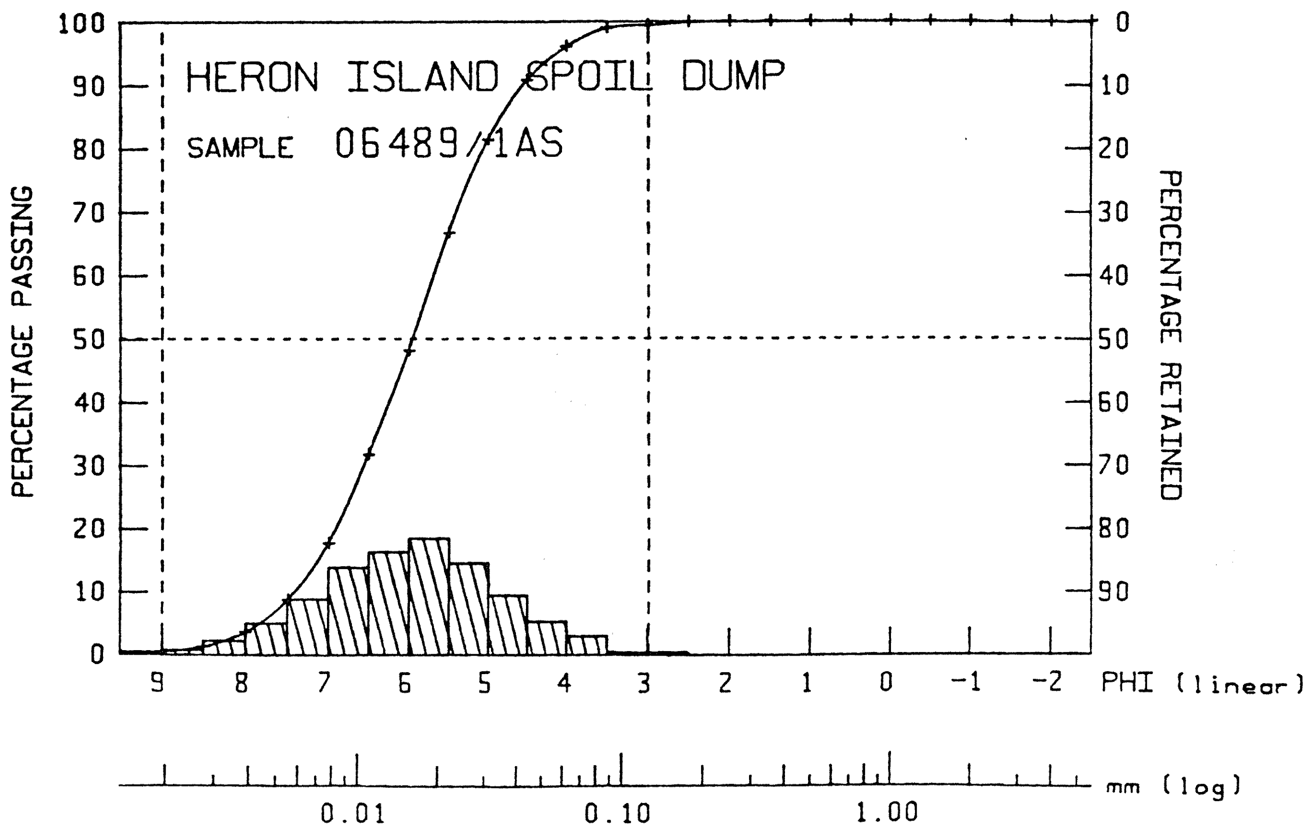


Figure F12. Silt deposited on reef flat close to spoil dump

PART TWO

Report on effects of Tropical Cyclone *Fran* March 1992

TABLE OF CONTENTS

FIGURES

1. INTRODUCTION

Heron Island is located in the southernmost portion of the Great Barrier Reef Marine Park (Figure 1). One of the most visited reef islands, it is the site of a tourist resort, a marine research station and a national park.

During late 1987, the then existing boat harbour, which had been constructed twenty years earlier by dredging a channel and mooring basin through the western end of the reef flat, was enlarged by further dredging and excavation. Considerable environmental disturbance was caused by silt released during this operation.

Material dredged from the harbour was deposited in a spoil dump which formed a reclamation on the southwestern shoreline of the island (Figure 2). The material stored in the spoil dump included some silt which was a cause for concern as subsequent natural events, including tropical cyclones, could erode the spoil dump and release further quantities of silt to contaminate the adjoining reef-top environment.

The Great Barrier Reef Marine Park Authority commissioned the authors of this report to undertake a monitoring programme of the spoil dump which continued until mid 1991. The results of that programme have been reported in a comprehensive report (Gourlay and Jell 1992) as well as in several shorter papers or articles (Gourlay 1991a, 1991b and Gourlay 1992).

This report deals with a subsequent extension of the original monitoring programme and concerns the effects of tropical cyclone *Fran* (March 1992) upon the spoil dump and adjoining reef flat. Monitoring of these areas after any severe event was recommended in the original report (Gourlay and Jell 1992, section 7.1).

For ease of comparison with the report on the previous monitoring programme, the same sequence and, where possible, the same headings and the same formats as were used in the previous report, are used to present the results of the cyclone *Fran* monitoring. However, matters common to both investigations, such as the history of the boat harbour and the geomorphic setting of Heron Island, as well as the details of the methods used in the various investigations, are not repeated in this report. For this information the reader should refer to Gourlay and Jell (1992).

2. HERON ISLAND AND TROPICAL CYCLONE *FRAN*

Tropical cyclone *Fran* developed near Vanuatu on 9 March 1992. It then moved westwards along latitude 20°S, passing just north of New Caledonia on 10 March, intensifying as it went (Figure 4). By 12 March, it had deepened to become a Category 4 tropical cyclone with a central pressure of 950 hPa and by 10 p.m. on 12 March it was located approximately 140 km northeast of Frederick Reef. At this stage interaction with a middle to upper level trough moving in from the west destroyed the convective system around the eye-wall causing the tropical cyclone to stall and weaken.

The cyclone, by now downgraded to Category 1 to 2, then continued to move towards the Queensland coast, taking a more southwestward course, and passed approximately 30 km to the east of Heron Island on the evening of 15 March. At about this time, the cyclone underwent a minor burst of intensification caused by interaction with the upper level trough leading to the development of an asymmetric windfield. The cyclone made landfall north of Bundaberg around 5 a.m. on 16 March after which it rapidly diminished in strength even though it moved out to sea again later on that day.

Some damage occurred along the Burnett coast and in northern Hervey Bay as a result of tropical cyclone *Fran*. In Bundaberg, 40 houses were unroofed and one was blown off its stumps by strong winds associated with the minor intensification of the cyclone around 9 p.m. on Sunday 15 March. At Burnett Heads, 14 km northeast of Bundaberg, there was damage to caravans, permanent housing and moored craft, three yachts were blown over at the marina and a trawler and a houseboat were sunk. The caravan park at Bargara, on the coast 15 km east of Bundaberg, was evacuated. There was flooding along coastal streams from Bundaberg to the Sunshine Coast as well as in parts of metropolitan Brisbane.

At Heron Island, winds were generally southeasterly during the period 10 to 15 March, rising from around 20 kn on 10 March, to 35 kn for most of the time on 14 and 15 March. On 15 March, the southeasterly winds exceeded 40 kn for almost six hours during the day, peaking at 45 kn between midday and 3 p.m. There was considerable damage to the *Pisonia* trees and many birds were killed, but no damage to buildings. During the evening of 15 March, the winds dropped and became more easterly as the unusually large eye of the cyclone (100 km diameter) passed by Heron Island. Overnight the wind strengthened again as it backed round to the westnorthwest and blew strongly, up to 40 kn, from this direction for three hours during the morning of 16 March as the cyclone crossed the coast. Over 60 mm of rain fell during the 24 hours up to 9 a.m. 16 March. As the cyclone lost its intensity after crossing the coast and then moved out to sea again, the winds backed further round to the southwest and windspeeds dropped to around 20 kn. By midnight on 17 March, winds were again southeasterly, blowing at about 15 kn.

Neap tides were occurring between 11 and 13 March as the cyclone approached Heron Island and substantial subtidal damage occurred on the western end of the northern side of the reef. Substantial damage to staghorn corals occurred and large *Porites* bommies were picked up and broken. Sand was moved around the reef flat. Shoreline erosion occurred at several places on the western end of the island. Specific locations of concern included the western end of the northern beach near the resort swimming pool, at the helipad, on the spoil dump at the jetty and for some distance further south of the jetty. After the cyclone, material had to be placed in front of both the resort swimming pool and the helipad to replace the material eroded by waves.

Offshore, the Wistari pontoon was moved to its cyclone moorings prior to the arrival of the cyclone. Nevertheless some damage was sustained by it. Further south, at Lady Musgrave Reef, a pontoon moored in the lagoon broke loose from its moorings and grounded on the reef, reportedly damaging some coral.

3. INVESTIGATIONS

3.1 Objectives

The objective of the monitoring programme described in this report was to determine the effects of tropical cyclone *Fran* (March 1992) upon the shoreline and reef at Heron Island with regard to the following matters:

(i) conditions affecting the spoil dump;

(ii) quantity of material stored in the spoil dump;

(iii) changes in shoreline in vicinity of spoil dump;

(iv) changes in reef-flat sediments.

3.2 Field Work

As in the previous monitoring programme, field work for this project was undertaken in two different ways:

(i) special site visit;

(ii) daily observations on site by Heron Island Research Station (HIRS) personnel.

Following cyclone *Fran* a site visit was made during 20 to 24 April 1992 by Dr Jell, assisted by laboratory technician Marshall Butterworth, and three final year civil engineering students, Darryl Bruce, Bobby Chisholm and Graham Jenkin.

Dr Jell and Marshall Butterworth collected sediment samples from the reef flat and boat harbour while the three students resurveyed the spoil dump. The latter work, together with other aspects of this monitoring exercise, forms the basis of the students' final year thesis project supervised by Dr Gourlay.

3.3 Sediment Analyses

Sediment analyses were undertaken to determine the nature of sediments on the reef flat and in the boat harbour after the cyclone, particularly the presence and extent of fine silt deposits.

A total of 145 samples was collected along traverses similar to those of the previous monitoring programme (Gourlay and Jell 1992, Figure 4) and ten were collected along the boat harbour and channel (Figure 17). Sampling and analysis procedures were also similar (Gourlay and Jell 1992, section 3.3).

3.4 Surveys of Spoil Dump Size and Shape.

The survey of the spoil dump size and shape was undertaken to determine the changes in its volume and shape since the previous survey in June 1991.

Survey methods and analysis were similar to those described in Gourlay and Jell (1992, section 3.4).

3.5 Hydraulic and Meteorological Data Analyses

The hydraulic and meteorological data analyses were undertaken to determine the actual conditions occurring during cyclone *Fran* so that the processes causing the observed changes to the shoreline and reef flat could be understood.

Continuing visual observations at stations 1 and 2 and at the jetty (Figure 2) were available for the period during which the cyclone affected the island. The quantities observed and other aspects of these observations are given in Gourlay and Jell (1992, section 3.5).

Additional meteorological data concerning cyclone *Fran* was obtained from the Bureau of Meteorology, Brisbane as well as the normal three hourly wind speeds and directions and daily rainfall data from the Heron Island automatic weather station. As previously, tide heights at Heron Island were predicted using Queensland Department of Transport tide tables. It should be noted that the tide board, installed on one of the jetty piles during April 1989 for this investigation, disappeared some time shortly before the night (or during the night) of 1-2 May 1992[1]. It has subsequently been reinstated.

The actual visual observations of the spoil dump and conditions affecting it have continued and are continuing since the cessation of the previous monitoring programme on 30 April 1991. Apart from examination of the conditions occurring during cyclone *Fran*, no significant analysis of this data has been or is likely to be undertaken in the near future because of lack of funds to do so.

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1 Delton Chen, University of Queensland, Department of Chemical Engineering. Personal Communication 16 June 1992.

4. RESULTS OF ANALYSES

4.1 Conditions affecting Spoil Dump during Tropical Cyclone *Fran*

4.1.1 Cyclonic Conditions affecting Coral Cay Beaches

In general, the magnitude of the waves generated by a cyclone depends upon the cyclone's intensity, size and speed of travel. The actual size of the waves offshore from Heron Reef during cyclone *Fran* will also depend significantly upon the position of the cyclone relative to the reef at the time under consideration.

During a cyclone or other meteorological event, the periods when wave energy reaches the beaches of a coral cay such as Heron Island are restricted to a series of subevents, each of which coincides with high tide. At low tides waves break on the reef edge, dissipating most of their energy there, and, while relatively large wave set-up may occur, negligible wave energy generally reaches the cay's beaches. At high tides wave set-up is relatively low but waves can reach the cay's beaches even though considerable energy may still be dissipated at the reef edge. For a given tide level the greatest amount of energy reaches the cay's beaches when waves just pass over the reef edge and reef flat without breaking and then break directly on the cay's beaches (Figure 3a).

On a horizontal reef top the maximum height of individual progressive waves is 0.55 times the water depth while the maximum significant wave height is about 0.4 times the water depth (Nelson 1992, Hardy *et al.* 1991a, 1991b). Hence the higher the tide, the higher the waves reaching the cay's beaches (Figure 3b). The effect of each subevent upon the cay's beaches thus depends primarily upon the height of the high tide but is also significantly influenced by the direction with which the offreef waves approach the reef edge and their subsequent refraction and shoaling over the reef topography.

The direction of approach to the cay's shoreline of the refracted offreef waves may be significantly different from the direction of any waves locally generated on the reef flat during the cyclone. The direction of the latter waves will be largely determined by local wind direction while their size will depend upon wind speed, water depth and the extent of the reef flat.

While the wave action reaching the spoil dump during the cyclone is modulated by the tide, the direct effect of wind action in blowing sand along the beach and off the spoil dump can occur at any time during the cyclone, provided the wind speed is sufficient to move the sand and the wind direction is favourable, i.e. generally aligned along the beach in one direction or the other. Onshore-offshore sand blowing will not be as significant on the narrow beaches of coral cays as it is on wider mainland beaches.

4.1.2 Specific Conditions occurring during Tropical Cyclone Fran

The following data and analyses have been used to determine the conditions produced by cyclone *Fran* at Heron Island and which caused the observed changes to the spoil dump.

(i) Visual observations at two locations (see Figure 2) on the spoil dump. Observations were made about an hour before the daytime high tide and included maximum and average breaker heights, average wave period, direction of propagation of breaking waves, water movement direction, occurrence of silt plumes, etc..

(ii) Predicted high and low tide levels from Queensland Department of Transport Official Tide Tables calculated from standard port at Gladstone.

(iii) Wind speed and direction (three hourly) and rainfall (daily) from Heron Island automatic weather station.

(iv) Cyclone track and synoptic charts supplied by Bureau of Meteorology.

(v) Hindcast wave heights, periods and directions offshore of the reef edge[2]

The path of cyclone *Fran* is shown on Figure 4 and the time series of conditions at Heron Island during the cyclone is shown on Figure 5. Average wave heights and silt plume widths at station 2 are shown on Figure 5.

As tropical cyclone *Fran* approached Heron Island and the strong south southeasterly to southeasterly winds developed, tides were low, with neap tides occurring on 11 to 13 March. Daytime high tides were 2m or less and the nighttime ones were about 2.5m. Breaking waves were higher (0.3 to 0.4m) at station 1 on the southeast side of the spoil dump than at station 2 near the jetty (0.2 to 0.3m). The breaking waves at station 1 were coming from the same direction (150°) as the wind and had periods of 1.5 to 2.8s. All waves were breaking on the edge of the reef to the southwest of the spoil dump and the reef flat was covered with white caps, *i.e.* breaking wind waves. The latter intensified as the wind velocity increased to 35kn and airborne spray was observed as these waves met incoming waves on the northern reef edge.

On 13 and 14 March the water over the reef flat was very cloudy from sediments and other materials stirred up by the breaking waves in comparatively low water depths (1 to 1.5m) on the neap high tides. On 14 March conditions on the reef flat were very rough as winds approached 40 kn at high tide during the afternoon. A heavy silt plume was observed originating from the scarp at station 2 and near the helipad behind the boat harbour. On 13 March rubble was exposed on the beach at station 1 and sand deposited on it at station 2.

At about 5 p.m. on 15 March winds were falling as the edge of the eye of the cyclone began to pass over Heron Island. Breaking waves at station 1 were 0.6 to 1m; these heights are equivalent to the largest significant waves and maximum individual waves possible on the reef flat at that time. "Enormous breakers" were observed breaking on the northern reef edge, although breaking wave directions at the spoil dump reflect the direction of the southeasterly locally generated wind waves. Waves of 5.4s were breaking in the boat harbour. Large waves up to 1.5m were observed at station 2, presumably caused by superposition of the two wave trains coming from opposite sides of the reef.

Wind erosion of the scarp at station 2 was noted and there was a streaky silt plume of the type associated with the rainy conditions which were occurring on 15 March. Water movement at the edge of the spoil dump was always northward during the southeasterly wind conditions.

When the eye of cyclone *Fran* passed by Heron Island on the evening of 15 March, the tides were approaching spring tide conditions. On the morning of 16 March, high tide at 6:40 a.m. was about 3m, and was beginning to ebb as the northwesterly winds peaked briefly at 40 kn at 9 a.m.

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2 This work was done by the three students for their thesis project. It is reported separately (Bruce 1992, Chisholm 1992, Jenkin 1992).

During the afternoon high tide of 2.7m on 16 March all waves were breaking on the reef edge. There were white caps on the reef flat and the breaking waves at both stations 1 and 2 were 0.8 to 1m, coinciding with maximum depth-limited conditions on the reef flat. Observed wave directions at both stations were westsouthwesterly, generally conforming with the direction of the locally generated winds. Wave periods were 2.9 to 3.5s. At station 2 there was also a second wave train of 4.8s waves coming from 275°, i.e. just north of west. These latter waves were presumably generated in deepwater to the north of Wistari Reef. A narrow silt plume was observed along the spoil dump shoreline and water movement at station 1 was now to the south. Erosion and recession of the scarp at the jetty were recorded but the waves were not reaching the base of the scarp. This erosion presumably had occurred during the preceding higher high tide of 3m which had occurred at 6:40 a.m. when winds were 35 kn from the westnorthwest.

On 17 March observations changed to the higher morning high tide (3.2m). Waves were no longer breaking on the reef edge but travelling over the reef flat to break directly on the beach face. The wave direction (220°) at both stations was the same as the westsouthwesterly wind direction. Wave periods were 2.2 to 3.5s. Breaking wave heights were higher at station 2 (0.5 to 0.7m) than at station 1 (0.3 to 0.6m). Moreover there was an underlying west to westnorthwesterly swell of 8.9s at station 2. A narrow silt plume was present and water movement at station 1 was to the south. A deposit of fine sand in front of the scarp at station 2 was noted. Accretion was occurring at station 1.

After the influence of the cyclone had died away on 18 March and southeasterly winds had resumed, waves were higher at station 1 (0.3 to 0.4m) than station 2 (0.2 to 0.3m). No waves were breaking on the reef edge. Water movement along the spoil dump shoreline was again northward and the silt plume was concentrated behind the boat harbour near the helipad. Waves were reaching the scarp in some places but not at the jetty. Photographs were taken of the spoil dump on 18 March.

During the cyclone there was significant sand blowing across the surface of the spoil dump. After the cyclone had passed, the surface was very rubbly as most of the fines on the surface had been blown away. On 17 March fine sand was observed to have accumulated in front of the erosion scarp on the south side of the jetty.

4.2 Quantity of Material in Spoil Dump

The plan of the spoil dump prepared from the April 1992 survey is shown on Figure 6. The volume of sediments stored in the spoil dump at April 1992 has been calculated from the same ten cross sections used for the previous calculations (Gourlay and Jell 1992, Figure 41). Table 1 updates Table 2 of the previous report, summarising the volume changes for the full period since the spoil dump was constructed. The quantity of material stored within the spoil dump is now calculated to be 15% less than in December 1987 at the completion of the boat harbour construction works.

Figure 7 shows the variation of spoil dump volume with time. It can be seen that, while the quantity of material stored in the spoil dump has been continually reducing, the rate of loss varies. This is a consequence of the fact that the loss is episodic, depending upon the occurrence of specific severe events to reshape the spoil dump. If the initial loss prior to May 1988 is ignored, the average rate of sediment loss from the spoil dump over the past four years has been $340m^3/a$.

Table 1. Quantity of Material in Spoil Dump

DATE	Volume relative to August 1984 m^3	Volume change m^3	Volume change since Dec. 1987 m^3
7 December 1987	14860		0
		-940	
14-17 May 1988	13920		-940 (6%)
		-300	
1-5 April 1989	13620		-1240 (8%)
		-390	
3-5 January 1990	13230		-1630 (11%)
		-70	
18-22 June 1991	13160		-1710 (11%)
		-600	
20-24 April 1992	12560		-2300 (15%)

There also has been some mechanical removal of material from the spoil dump. For example, the hole from an excavation made in the top of the spoil dump for fill to restore the eroded beach in front of the resort swimming pool can be clearly seen on Figure 6. The volume of this excavation is, however, quite small, i.e. about 4m^3.

Volume change calculations have now been extended eastward from the spoil dump for a distance of 80m (four profiles at 20m spacing) almost to the western end of the beach rock. Figure 8 shows the total volume of sediment stored within the spoil dump and the adjoining beach in front of the research station. The baseline and baselevel for the calculations and the scales of the graphs (Figures 7 and 8) are the same.

Apart from June 1991, the total volume of sediment in the extended area has remained virtually constant. The difference between the maximum and minimum volumes is 318m^3 which is 0.6% of the total volume or 2.1% of the initial spoil dump volume. It is also less than the average annual loss of 340m^3 from the spoil dump. However, the increase in volume between June 1991 and April 1992 indicates that there has been a net gain of material in the extended area during that period. Comparison of the three graphs, Figures 7, 8 and 9, shows that this accumulation has largely taken place within the additional 80m east of the spoil dump, below the research station. Still further east of the spoil dump, Figure 46 in Gourlay and Jell (1992) indicates that there was an overall small accumulation of material in the area examined between the time of construction of the spoil dump and March 1990. The rate of this accumulation has varied and has been shown to be event dependent.

Considering the spoil dump only, Figure 9 shows that, between June 1991 and April 1992, material was removed from the central portion between profiles 4 and 7 and that a smaller amount of material was deposited at both ends.

4.3 Changes in Spoil Dump Shoreline during Tropical Cyclone *Fran*

Between June 1991 and April 1992 there has been significant re-alignment and re-shaping of the spoil dump beach (Figures 10,11 and 12). This includes erosion in profiles 1 to 7, particularly of the spoil dump surface and the upper beach, and deposition in profiles 1 to 3 and 8 to 10. The 4m contour has retreated between profiles 4 and 7 by up to 5m. The erosion has continued to expose the fine silt layers in low escarpments near the jetty.

Some of the vegetation growing on the spoil dump in 1991 was no longer there in April 1992. The 1992 survey records only one *Casuarina* whereas three were recorded in June 1991. It is known that one of these disappeared during cyclone *Fran*.

The HIRS coastal observations indicate that most of the erosion of the spoil dump during the period June 1991 to April 1992 actually took place during cyclone *Fran*. Figure 13 shows the amount of retreat of the erosion scarp at the jetty, since the construction of the spoil dump. Conditions caused by cyclone *Fran* resulted in the erosion scarp in this area receding by 3.2m.

It is not known when the deposition immediately to the east of the spoil dump occurred, it may have occurred continuously over the whole period or it may be related to a specific event, which may or may not have been cyclone *Fran*. As mentioned in the previous section, Figure 8 indicates a net increase in volume of the extended area between June 1991 and April 1992. This can only have occurred if material has been added to the system. Consequently it seems probable that the spoil dump is acting as a groyne, trapping sediment as it is moved alongshore in a westward direction along the southern beach. This westward alongshore movement would be caused by waves coming from a southeasterly direction. There was a prolonged period of southeasterly waves as cyclone *Fran* approached Heron Island, this was during a period of neap tides when the smaller waves associated with the lower tides were likely to be constructive. Accretion has occurred mainly at around the 2.5m level.

In addition to erosion of the spoil dump during cyclone *Fran*, there was substantial erosion behind the boat harbour which threatened to undermine the helipad. After the cyclone, material was placed in front of the helipad.

4.4 Changes in Reef Flat Sediments

The major effects of cyclone F*ran* on the reef-top sediments around Heron Island cay were:

(i) To throw up considerable amounts of coarse rubble of *Acropora* sticks and plates onto the margins of the reef northwest of the boat harbour and along the northern reef edge.

(ii) To release significant quantities of sand and silt size material from the spoil dump (see section 4.2).

(iii) To redistribute the sediments already on the reef flat and to winnow the finer fraction.

Overall the width of the rubble zone paralleling the reef edge is greater. Several small rubble banks have developed along the reef crest between the entrance to the harbour and the western tip of the reef. The graphic mean size, the graphic standard deviation and silt content plots compared with those of December 1989 show that over this period the mean size has increased, the sediments generally are better sorted, and there has been a decrease in the silt content right across the reef flat (Figures 14 to 16).

The sediments of the harbour and the entrance channel were sampled and contain significantly greater proportions of silt and clay size material than the reef flat sediments. In the harbour and the inner part of the channel the surface sediment is somewhat variable, possibly due to the stirring up of the bottom sediments by the boats at low tides. In the harbour, the silt and clay content is up to 14% and in the channel it decreases from about 7% in the inner part to less than 1% at its entrance. The harbour appears to be one sink for the fines from the spoil dump. When compared with data from the December 1989 survey, there seems to have been a decrease in the silt and clay content in the harbour and channel (Figure 17).

5. CONCLUSIONS

Heron Island was threatened by tropical cyclone *Fran* during March 1992. The cyclone with a minimum central pressure of 950 hPa on 12 March passed 30 km east of the island at 6:00 pm on 15 March. Fortunately for Heron Island, by this time the cyclone had lost some of its earlier intensity and the central pressure had risen to between 980 and 990 hPa.

As the cyclone was approaching the island, southeasterly winds gradually increased from 15 to 20 kn on 9 March to over 40 kn on 15 March. During this period there were neap tides, but by 15 March, the early morning high tide had a predicted height of nearly 3m. On 15 March, winds exceeded 40 kn from the southeast, peaking at 45 kn between midday and 3 p.m. when the tide was low. During the evening of 15 March, the eye of the cyclone passed 30 km east of Heron Island and the winds dropped to less than 20 kn, swinging round, first to the east and then backing round to westnorthwest. On the morning of 16 March, high tide reached about 3m and the wind was strengthening again to over 35 kn, but this time from the west. After this time, the cyclone moved onshore, crossing the coast near Bundaberg, and the winds rapidly decreased in strength, even though the cyclone subsequently moved offshore again.

During the period when the cyclone was approaching Heron Island, the water on the reef flat became very cloudy as sediment was stirred up by breaking waves in the comparatively low water depths during neap tides. As the wind and wave direction was from the southeast during this time, the spoil dump beach was protected from the full force of any wave attack due to its location. After the cyclone had passed Heron Island, the spoil dump became more vulnerable. The winds had backed round to a westerly direction and the high tide levels had increased. This combination led to substantial erosion at the jetty and below the helipad releasing considerable silt onto the reef flat. After the cyclone had dissipated it was noticed that there had been substantial wind erosion of the surface of the spoil dump. The surface had become very rubbly with much of the fine sediment having been winnowed from it. Furthermore there was some deposition of fine material in front of the newly formed erosion scarp.

On the reef, more coral rubble is now present on its western edge and silt has been winnowed from most of the reef-top sediments. There has also been a decrease in the silt content of the surficial channel and boat harbour sediments.

The beach to the east of the spoil dump has accreted. This was probably caused by southeasterly waves moving sediment alongshore in a westerly direction, and may or may not have been a result of cyclone *Fran*.

Overall, at Heron Island, even though there was beach erosion and considerable release of silt from the spoil dump during cyclone *Fran*, there was very little effect on the reef flat from the spoil dump. There was no significant accumulation of fines on the reef and consequently it is unlikely that there was any deleterious effect to the flora and fauna. Furthermore, between December 1989 and April 1992 there has been a continuation of the trend of winnowing fines both from the reef-top and the boat harbour.

It was most fortunate for Heron Island that tropical cyclone *Fran* had lost much of its earlier intensity before it came close to the island, otherwise the effects of the cyclone might have been much more severe. It was also fortunate that the tides were not particularly high for most of the time that Heron Island was threatened by cyclone *Fran*.

Finally, the impacts of cyclone *Fran* upon the spoil dump and adjoining reef are consistent with the conclusions of the previous report (Gourlay and Jell 1992, sec. 6.1, para.4). Significant erosion and loss of material occurs episodically during severe events such as when a cyclone is in the vicinity of the island (e.g. cyclone *Fran* - March 1992) or from heavy swells produced by distant weather systems (e.g. cyclones *Aivu* - April 1989 and *Joy* - January 1991). Furthermore, there has been no build up of fine material on the reef-top as a consequence of the cyclone. On the contrary cyclone *Fran* has continued the process of removing fine material from the reef-top.

6. RECOMMENDATIONS

(i) Since significant changes may occur during cyclonic events and the effects of the latter upon a cay's shoreline vary widely depending upon tide height and cyclone intensity and direction, the spoil dump should be resurveyed and the reef-top sediments resampled following any significant cyclone or other event so as to determine the impacts of that event upon the spoil dump, the adjoining reef-top and the boat harbour.

(ii) The recommendations of the previous report (Gourlay and Jell 1992, Chapter 7) should be reviewed in the light of present and anticipated management needs. Definite steps should be taken to implement those of them which will significantly contribute to the effective management of Heron Island and its reef.

7. ACKNOWLEDGEMENTS

The assistance of the Bureau of Meteorology, Brisbane Regional Office, is acknowledged in providing data obtained from the Heron Island Automatic Weather Station as well as data and information on tropical cyclone *Fran*.

The sediment analyses were carried out by Marshall Butterworth (Department of Earth Sciences). Figures 1, 2, 3 are from the earlier Report (Gourlay and Jell, 1992). Figure 13 has been updated from the earlier Report by Reg Stonard (Department of Civil Engineering) who has also prepared Figures 4 and 6. Figure 5 was prepared by Graham Jenkin and Figures 7 to 12 by Darryl Bruce, with the assistance of Jennifer Hacker. Elvira Burden (Department of Earth Sciences) drafted Figures 14 to 17 and Ann Sellars (Department of Civil Engineering) prepared the text.

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FIGURES

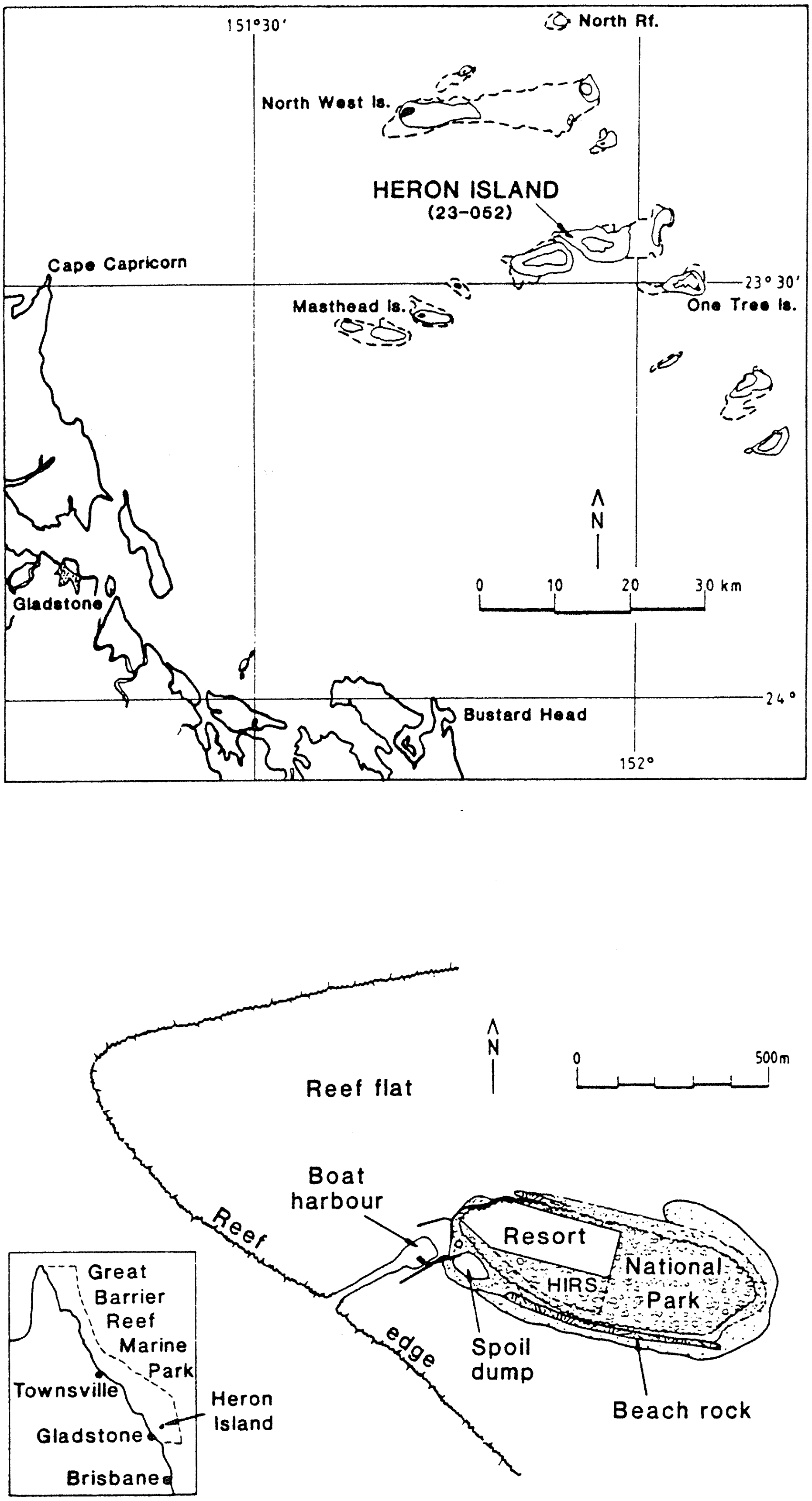


Figure1. **Location of Heron Island**

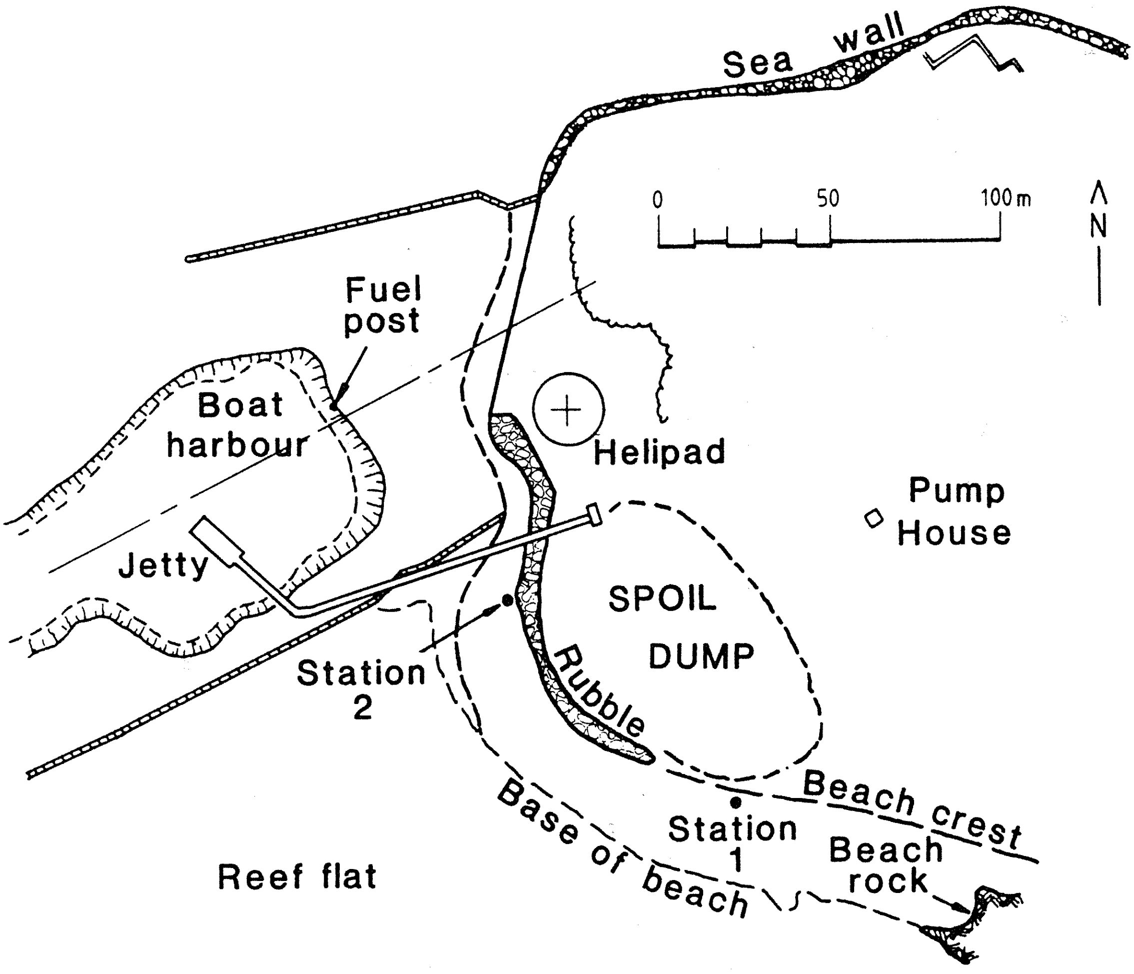
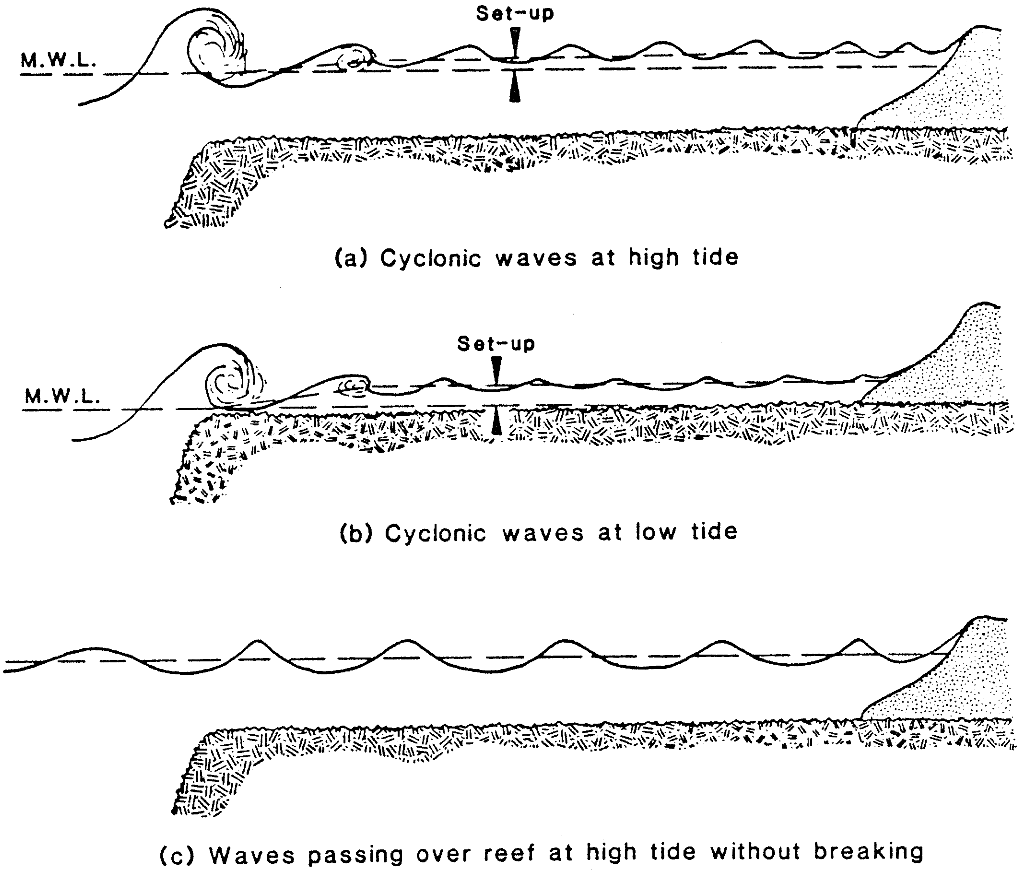
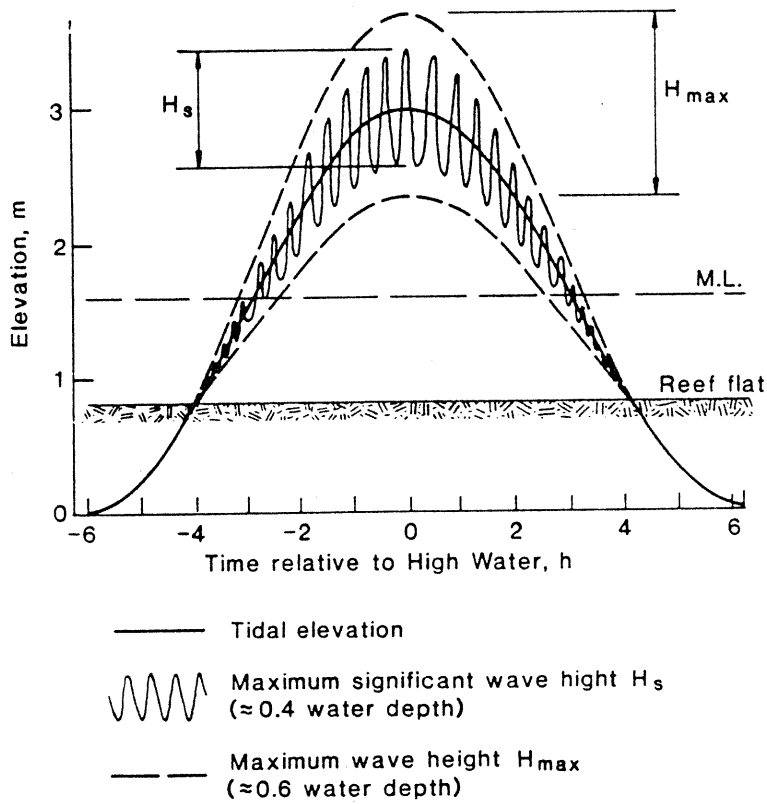


Figure 2. **Location of spoil dump and observation stations**



(a) Wave breaking on reef platform under different tidal conditions



(b) Effect of tidal cycle upon reef-top wave heights

Figure 3. Reef top waves and tidal conditions

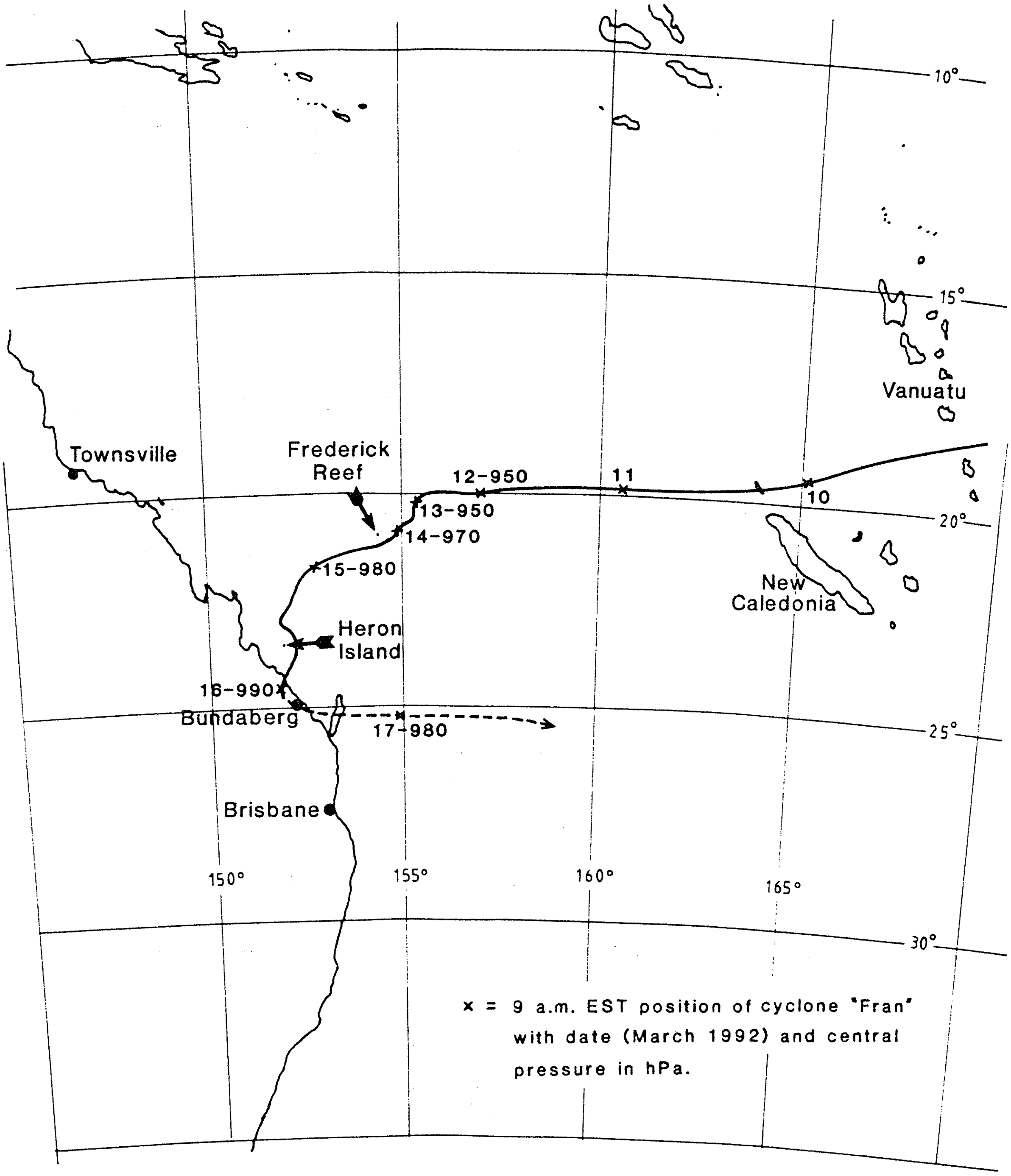


Figure 4. **Track of tropical cyclone *Fran*, 11 to 17 March 1992.**

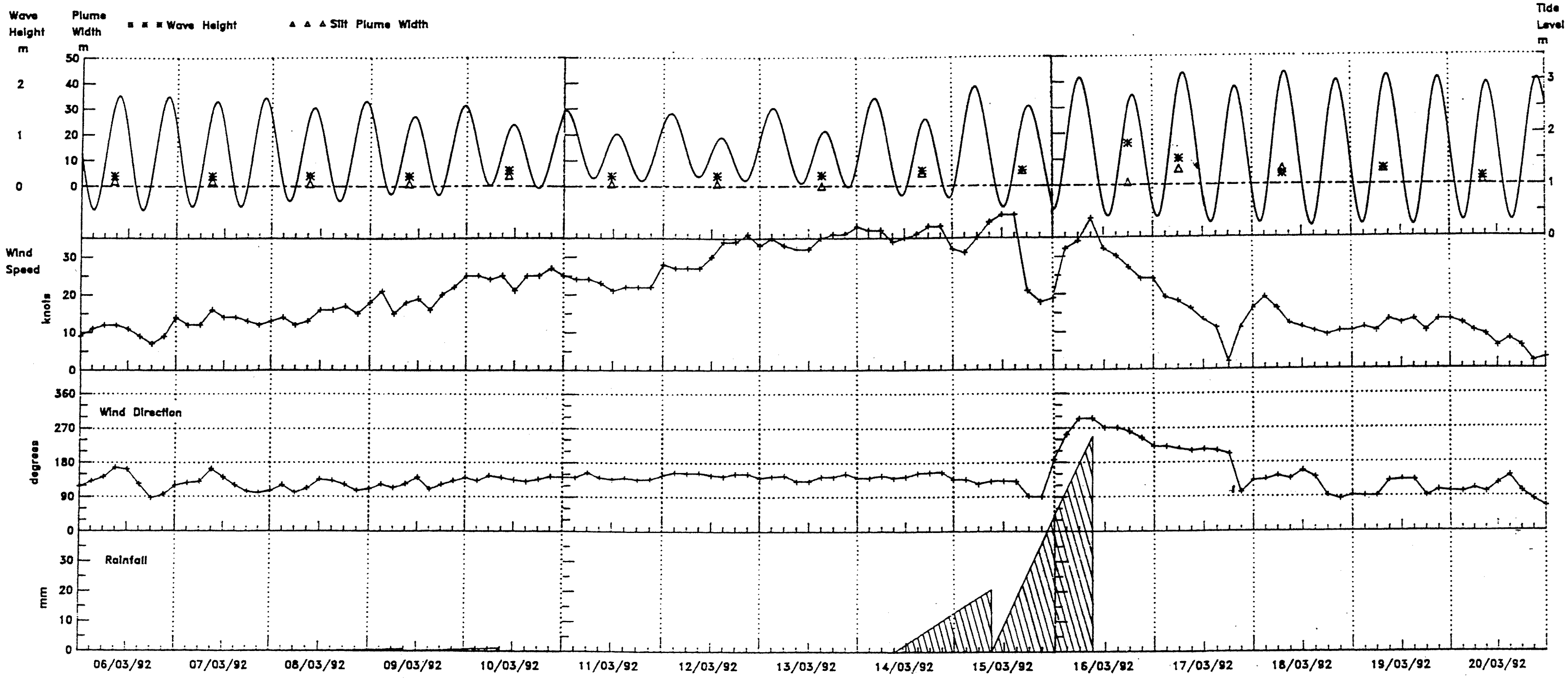


Figure 5. Tropical cyclone *Fran* event, 6 to 20 March 1992

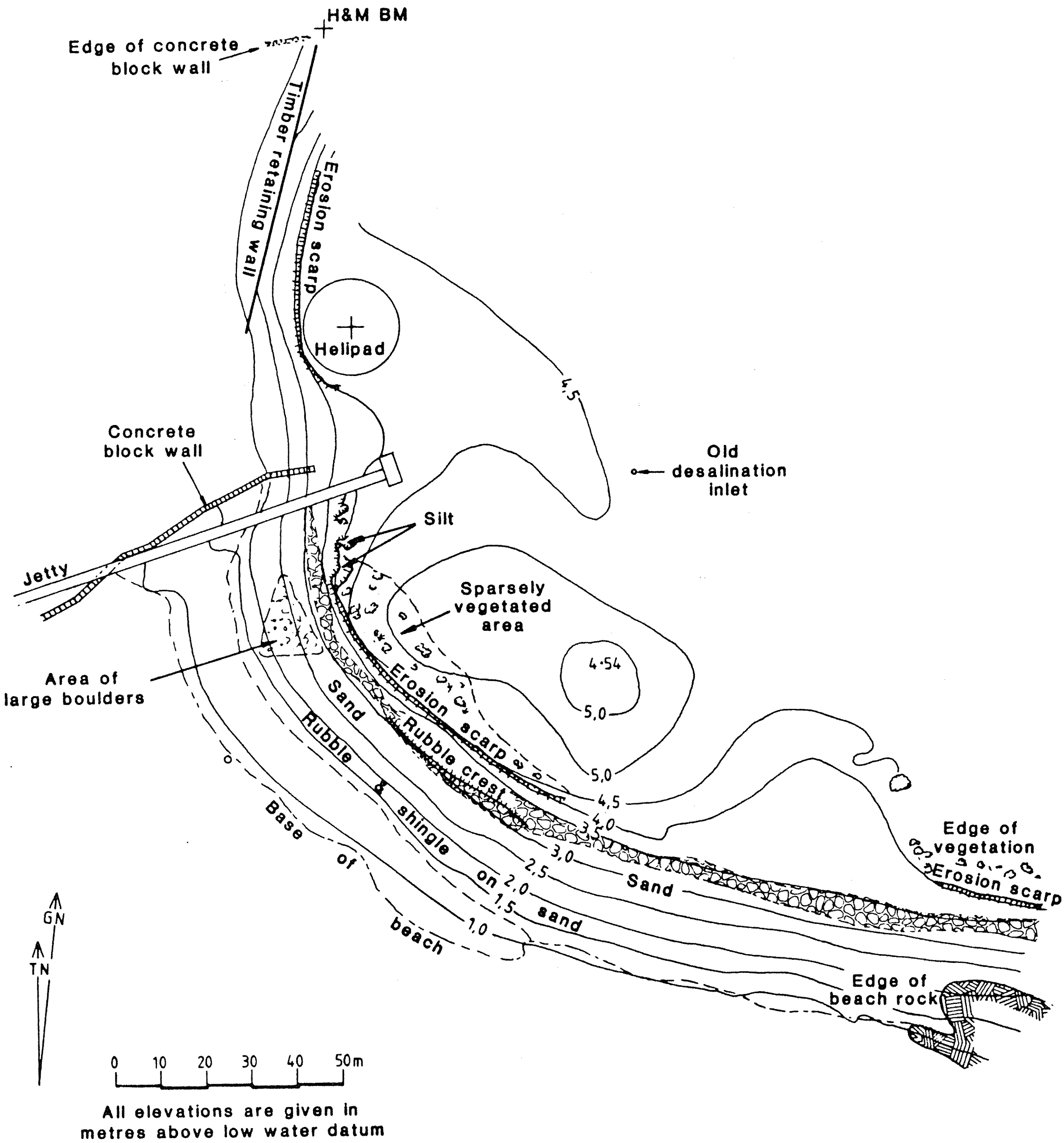


Figure 6. Spoil dump - April 1992

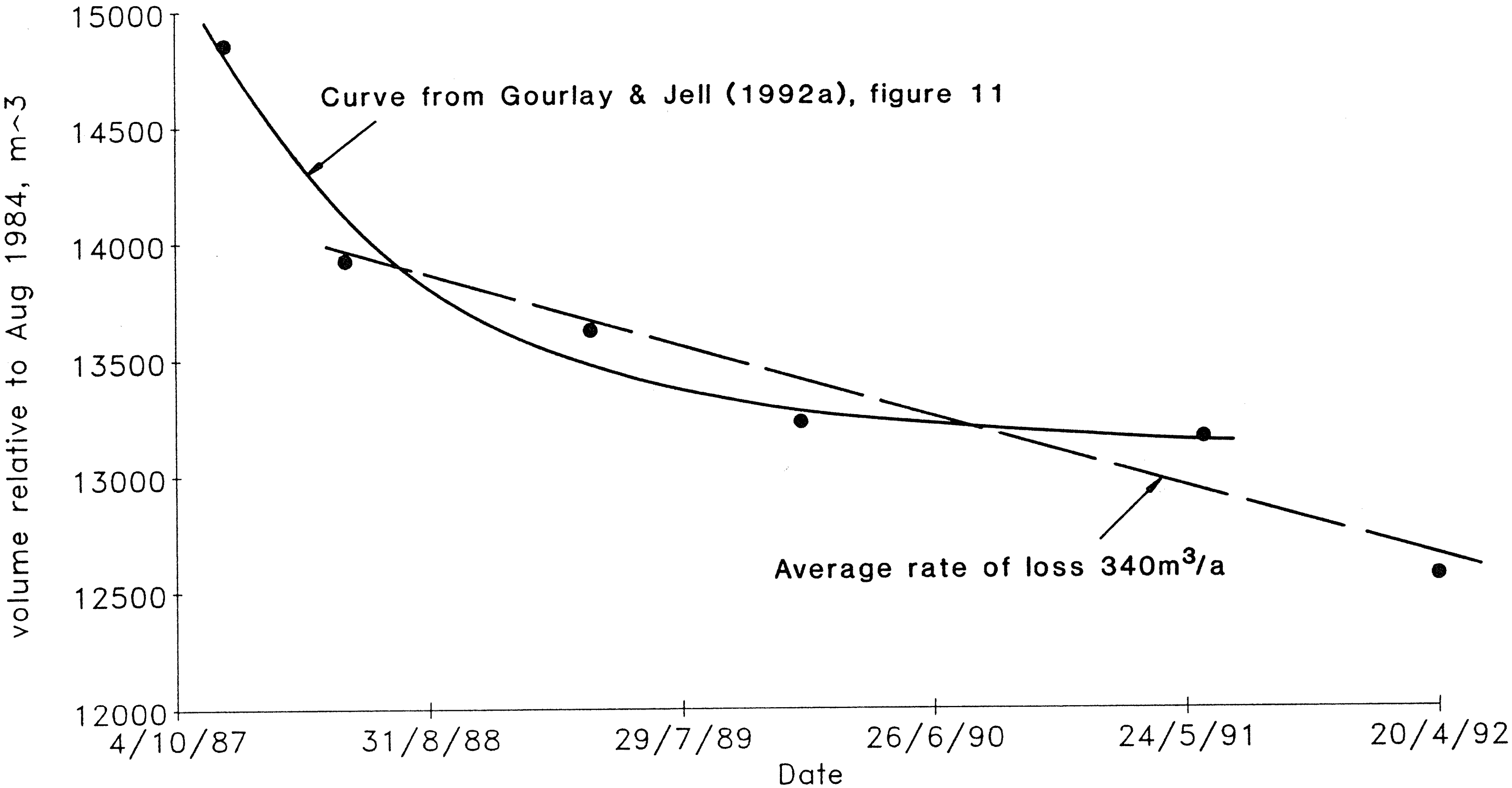


Figure 7. Changes in spoil dump volume - December 1987 to April 1992

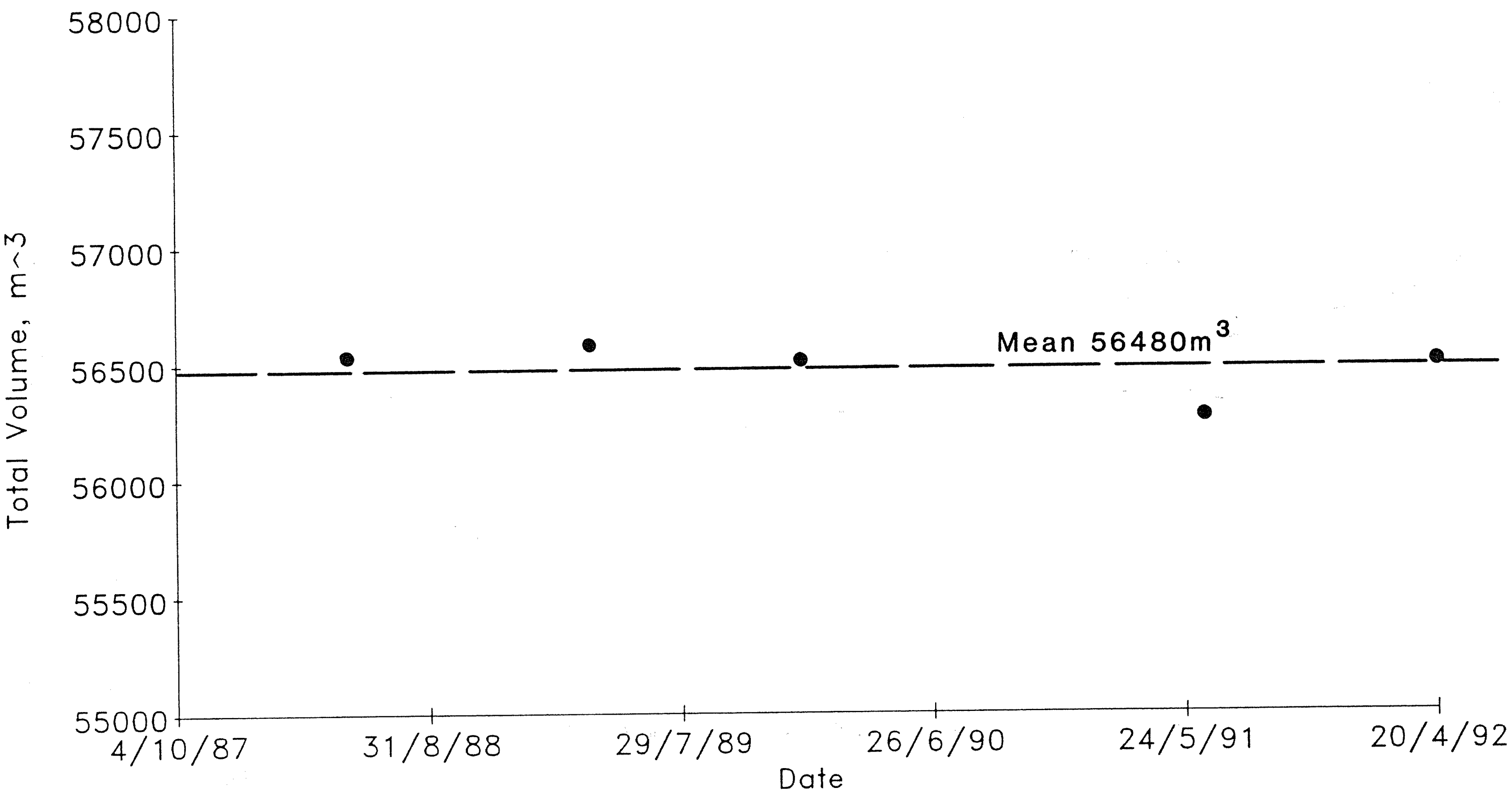


Figure 8. Volume of material in extended spoil dump area (including four extra profiles east of spoil dump) - December 1987 to April 1992

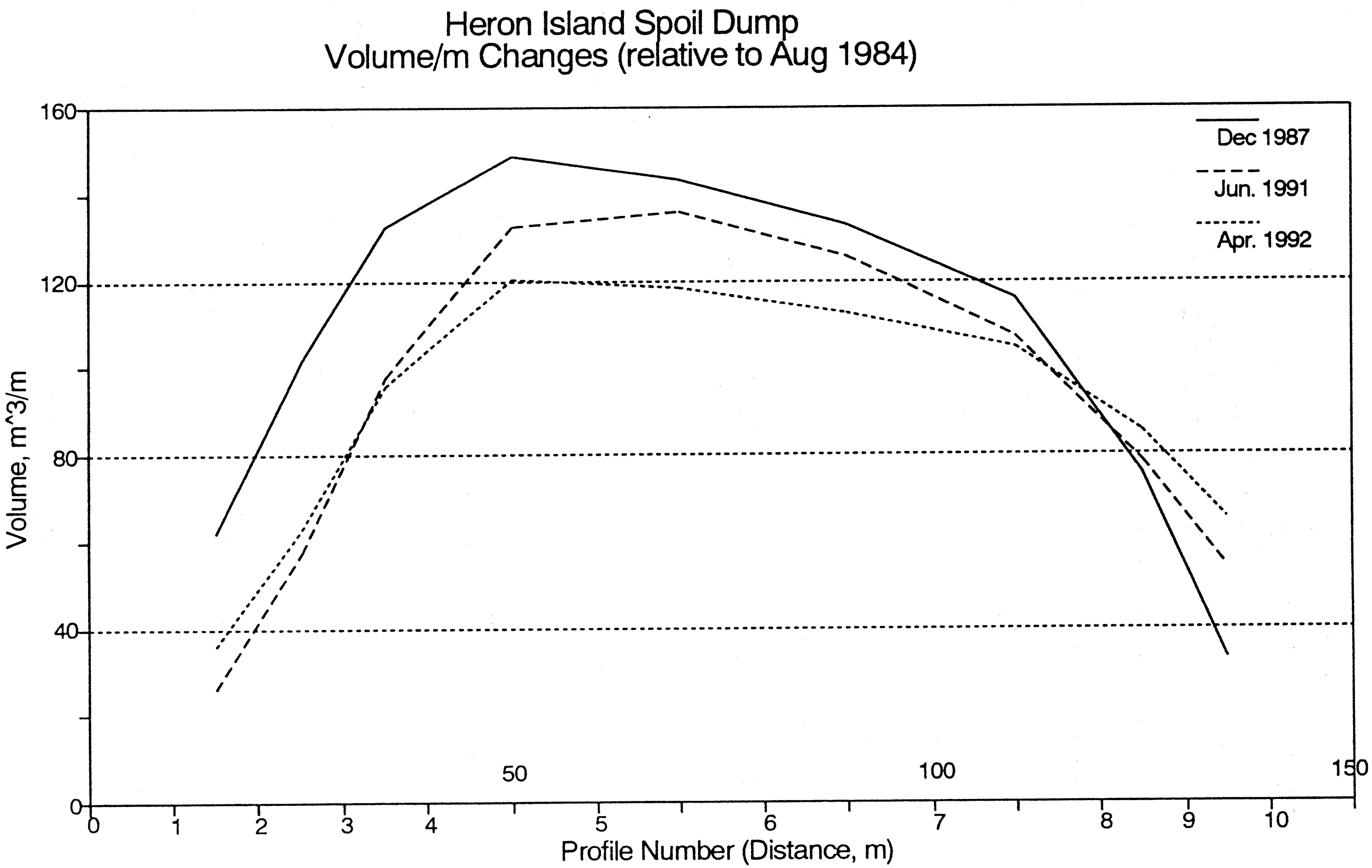


Figure 9. Volume changes along spoil dump relative to August 1984

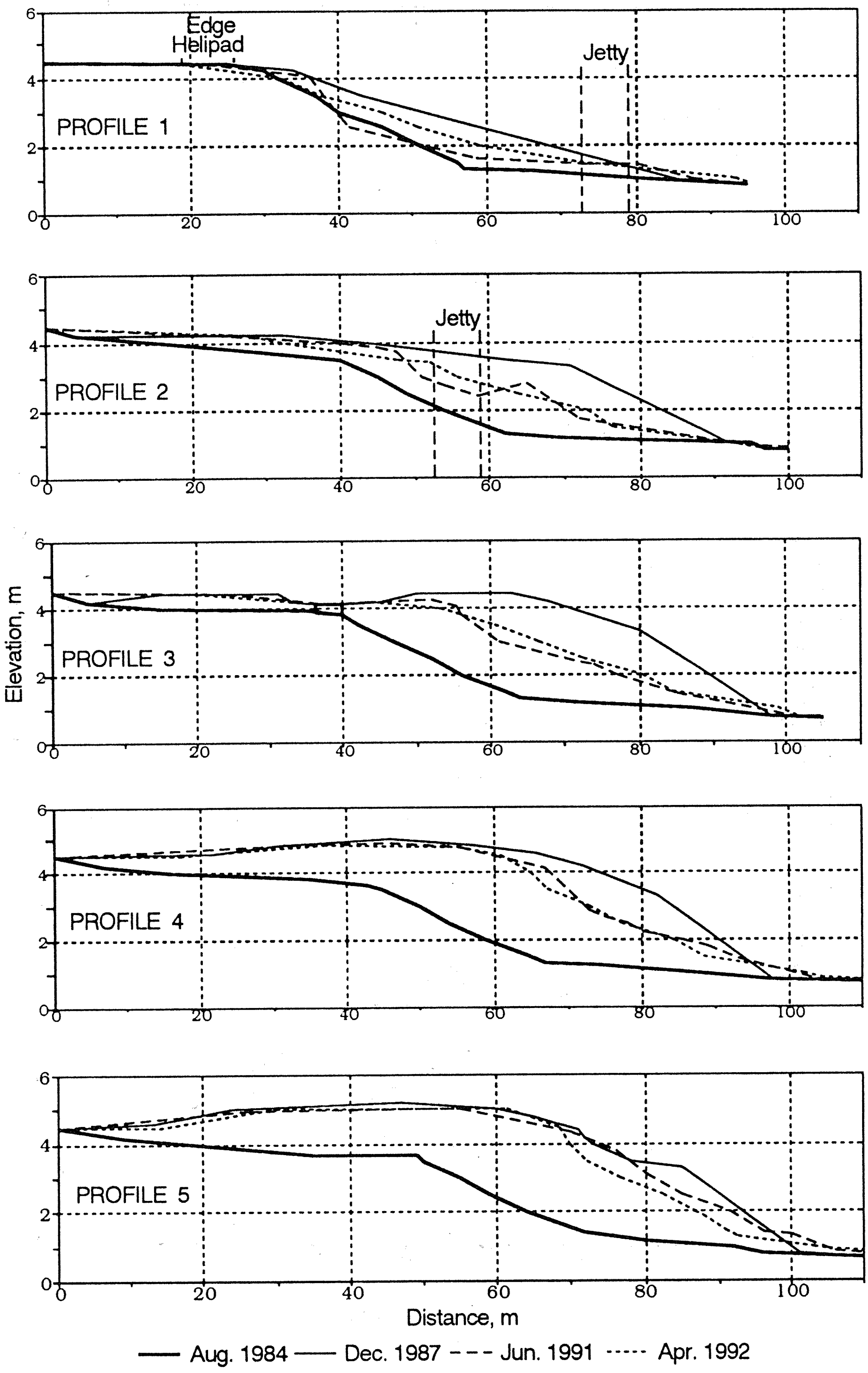


Figure 10. Spoil dump profiles 1 to 5

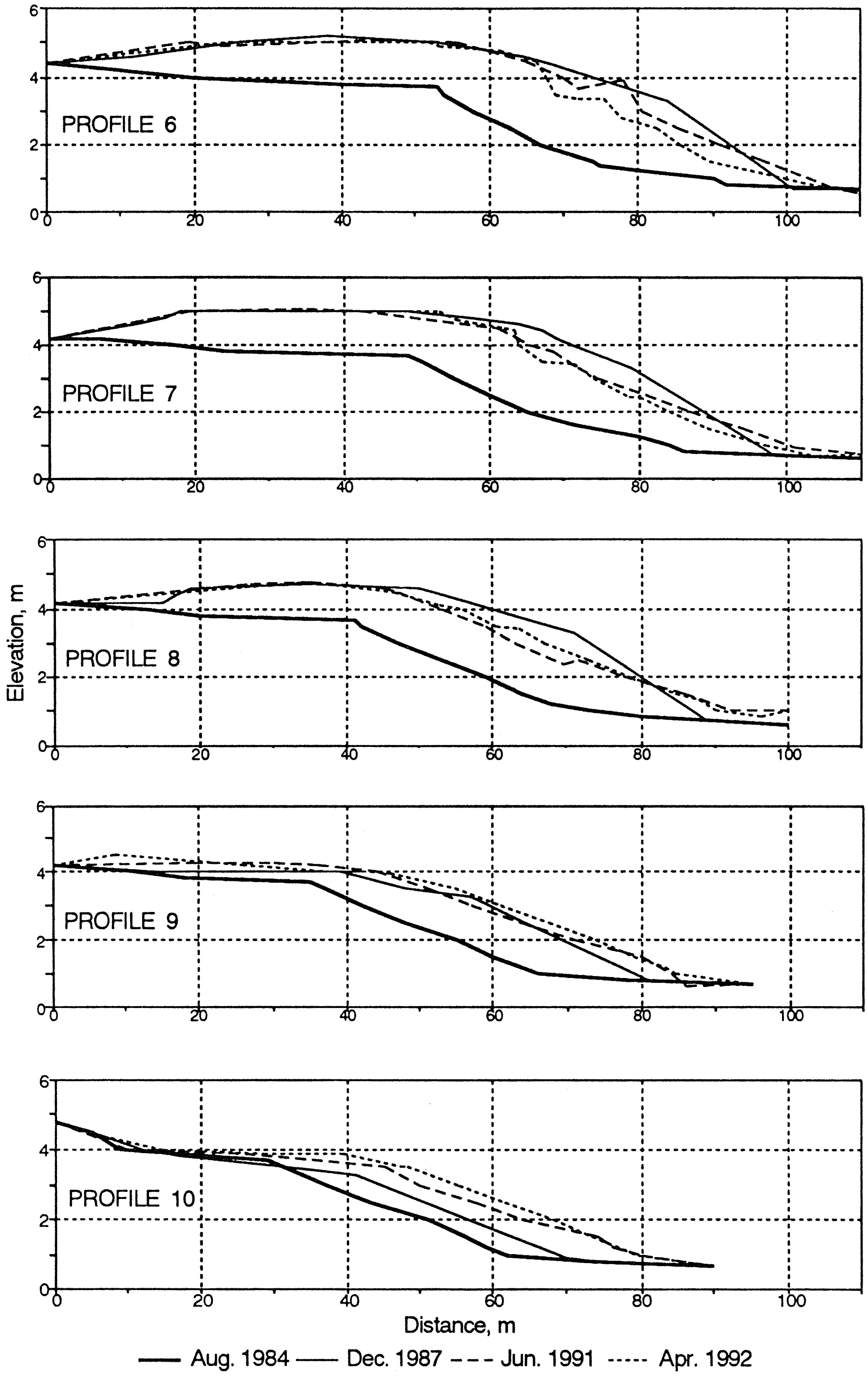


Figure 11. Spoil dump profiles 6 to 10

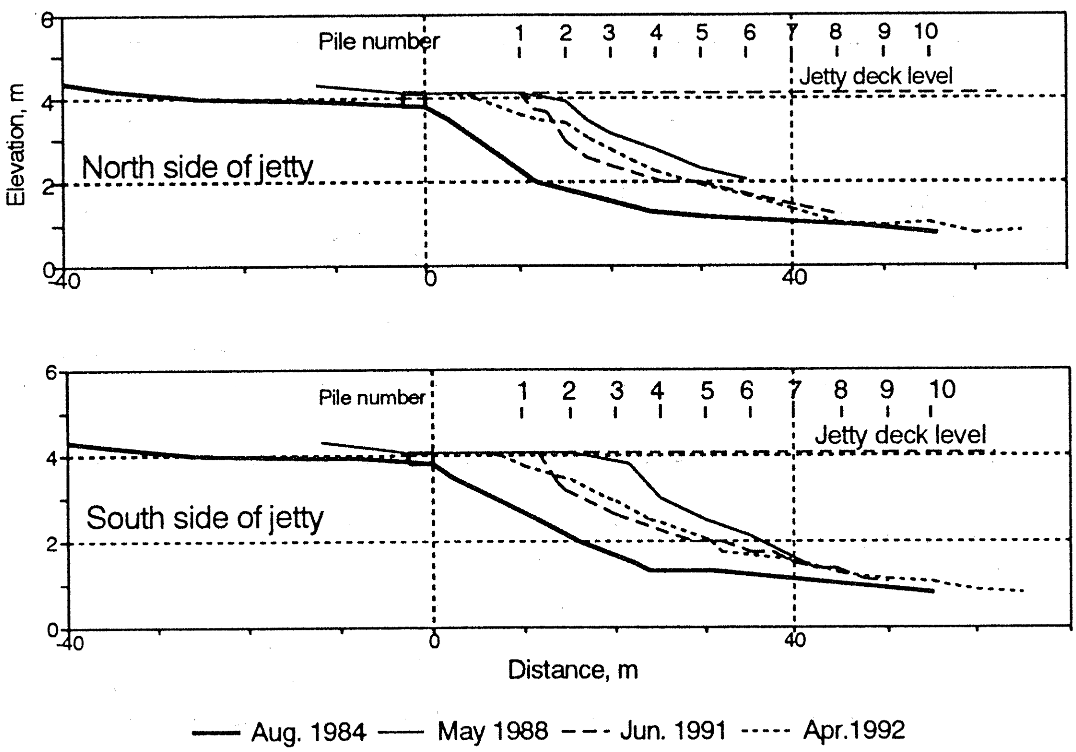


Figure 12. Beach profiles at jetty

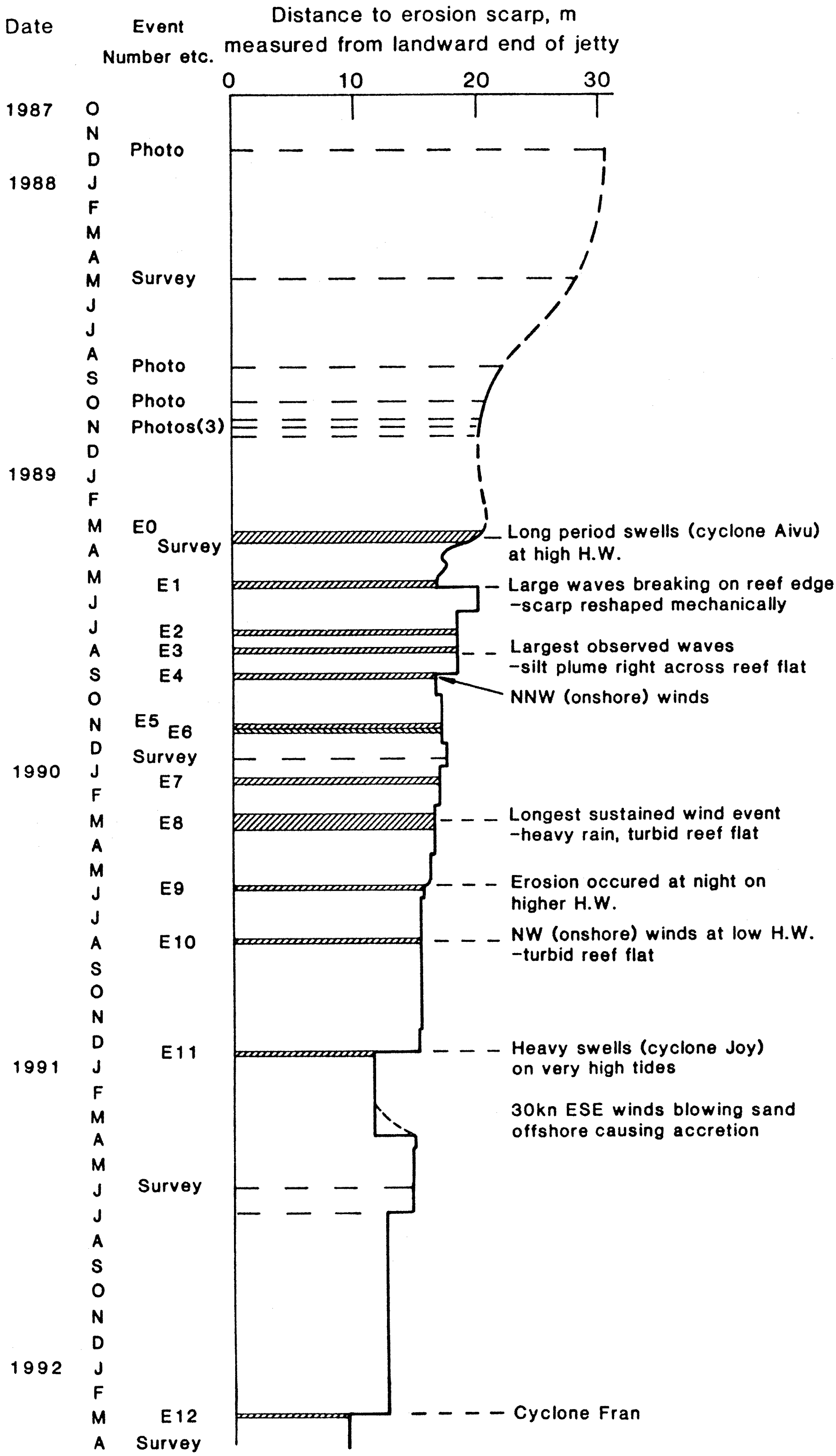


Figure 13. Erosion scarp position along southern side of jetty

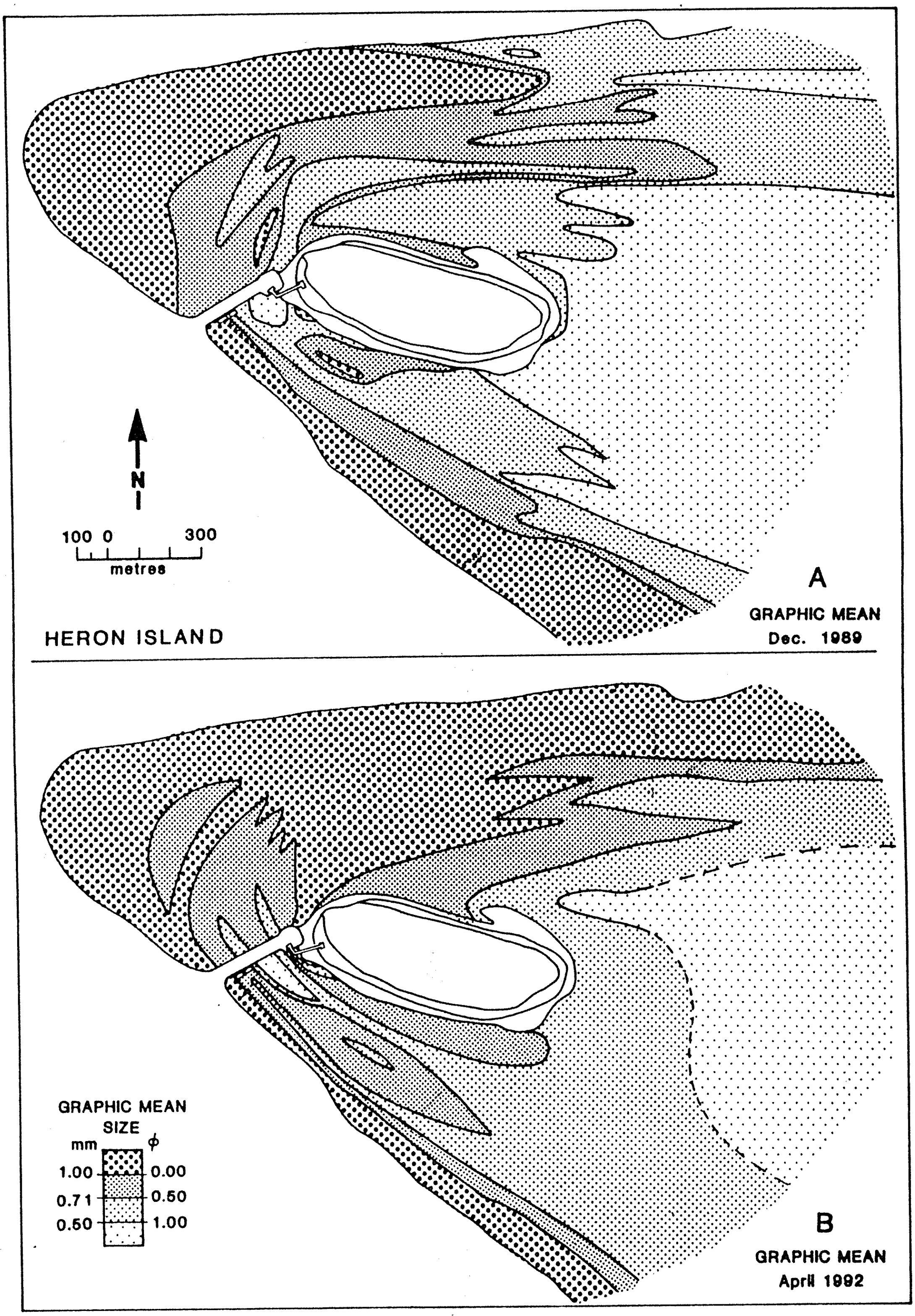


Figure 14. Distribution pattern of median size (graphic mean) coefficients for sediments - December 1989 and April 1992

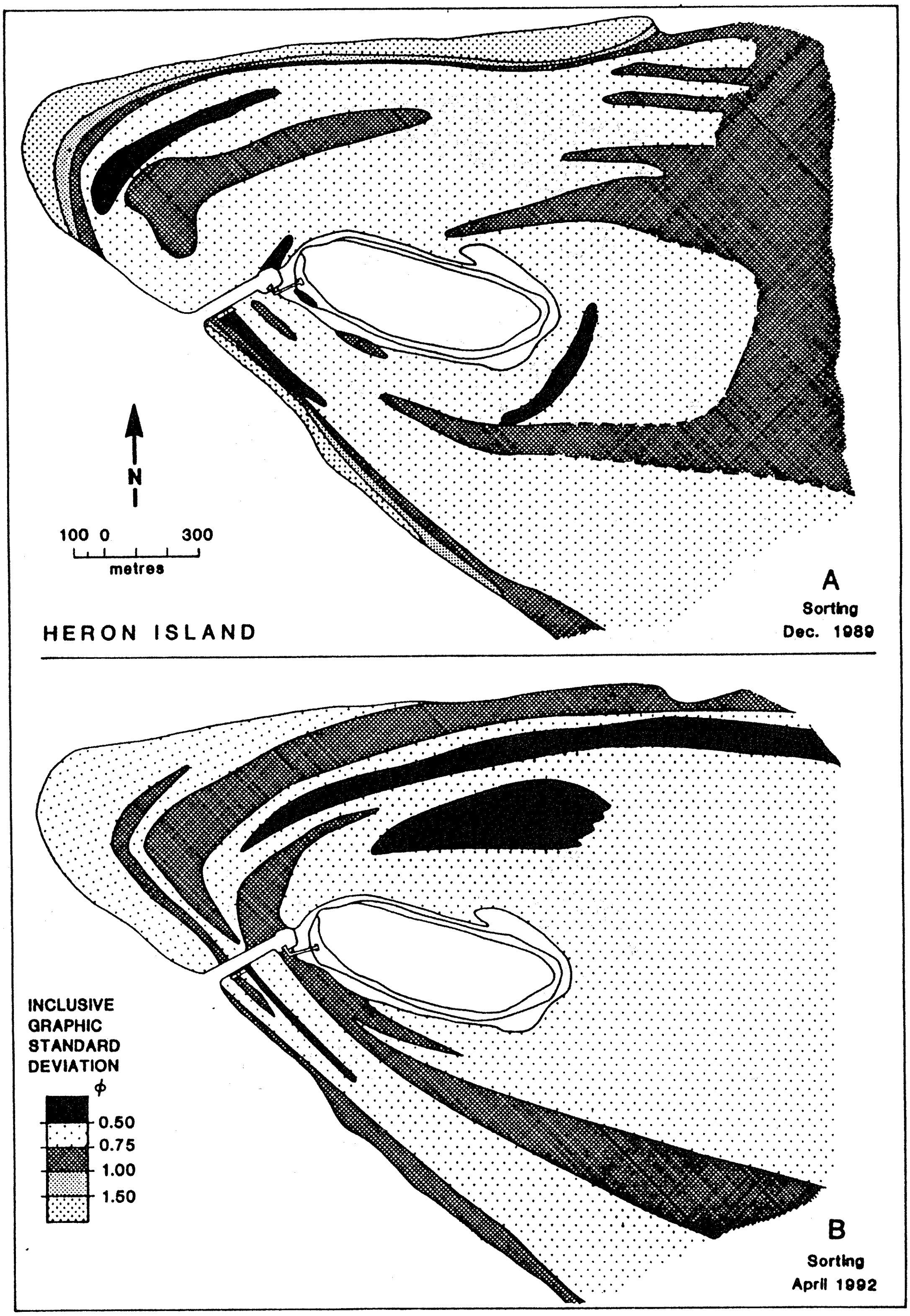


Figure 15. Distribution pattern of sorting (inclusive graphic standard deviation) coefficients for sediments - December 1989 and April 1992

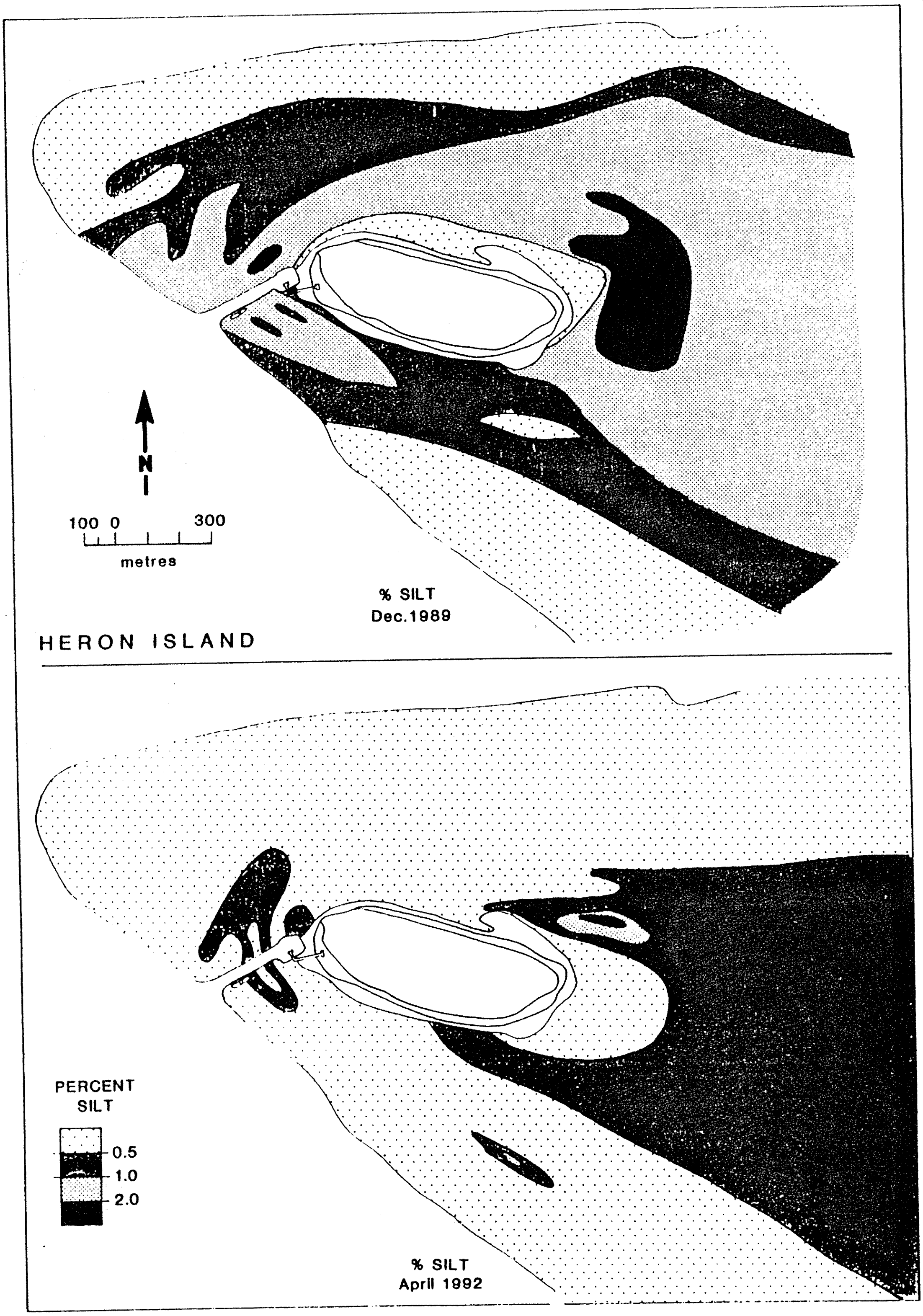


Figure 16. Distribution pattern of silt fraction (% of total sample) of sediments - December 1989 and April 1992

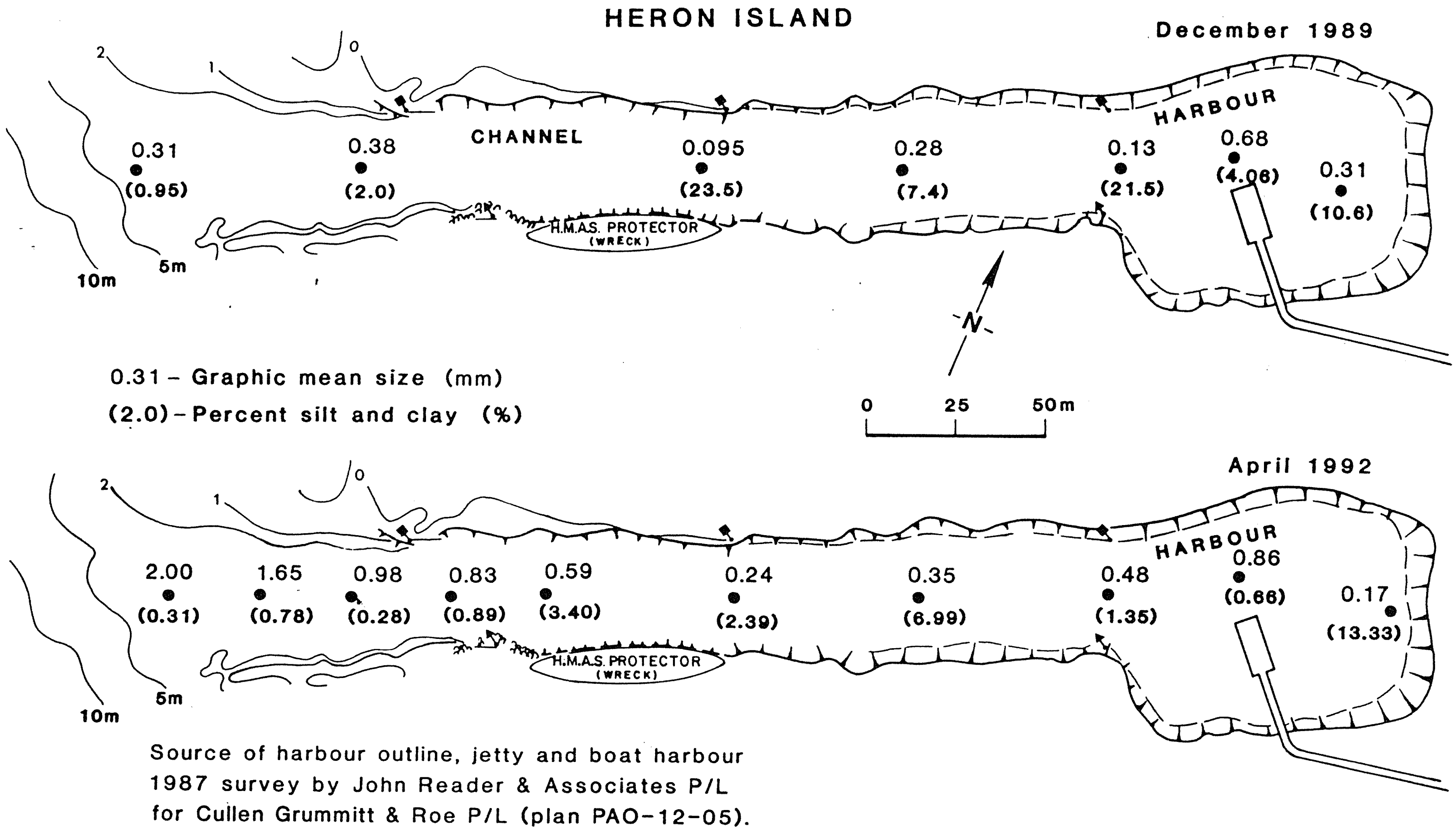


Figure 17. Distribution of median size (graphic mean) and silt and clay content of harbour and channel - December 1989 and April 1992