DEEP BIOTURBATION BY AXIUS SERRATUS
IN THE STRAIT OF CANSO, NOVA SCOTIA

DEEP BIOTURBATION BY *AXIUS SERRATUS*
IN THE STRAIT OF CANSO, NOVA SCOTIA

by

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ABSTRACT

The thalassinid crustacean Axius serratus, was investigated in order to better understand its ecology and effect on the sediment, in the Strait of Canso, Nova Scotia. The shrimp, previously virtually unknown from Canadian waters, was found to be a common element of the benthic biota south of the Canso causeway. Axius exploits vast areas of sediment, and establishes semi-permanent burrows. Densities in the study area average from 9 to 15 per square meter and uniform spatial distributions were noted.

Areas subject to heavy industrial pollution, termed barren zones, contain no forams, ostracods or molluscs. Axius serratus is the only invertebrate observed living in the barren zones, and may well serve as an indicator of water quality.

Polyester resin casts show that the burrows are open to a depth of at least 2.9 m. - the deepest bioturbation event recorded. Burrows are lined with grass, and exhibit a knobby exterior similar to that of Ophiomorpha nodosa.

Variations and trends in the mass physical properties of the sediment of the Strait of Canso are related to the distribution of Axius

burrows. Sediment adjacent to burrows shows relatively higher values for grain density and mass unit weight. Effect is at maximum near burrow opening.

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CHAPTER ONE

INTRODUCTORY CONSIDERATIONS

A. Scope and Objectives

In 1954, a causeway was constructed across the Strait of Canso, linking Cape Breton Island with mainland Nova Scotia. In the summer of 1973, scientists from the Atlantic Geoscience Centre undertook a multidisciplinary study of the effects of the causeway on the physical and ecological parameters of the Strait. In addition to the environmental impact study (Buckley *et al.*, 1974), papers dealing with the distribution of Foraminifera (Cole and Ferguson, 1975; Vilks *et al.*, 1975), Ostracoda (Cole and Ferguson, 1975), Mollusca (Wagner, 1975) and the geotechnical properties of the subsurface sediments (Brown and Rashid, 1975) were also published.

During the course of the original study, a live shrimp was found intact in its burrow 10 cm. below the surface of a core from Eddy Point on the south side of the causeway. The burrow continued the length of the 110 cm. core. Subsequent analysis revealed that all the cores taken south of the causeway contained burrows. Filled burrows penetrated by the core sampler appear as oval or semi-circular patches of reddish-brown sand, similar to the surface sediment. The shrimp was later identified as Axius serratus, Stimpson 1852, a species rarely encountered on the Atlantic coast of North America. This study examines the aspects of the ecology of Axius serratus.

The study of animal-sediment relationships has recently received considerable attention (Frey, 1975). Sedimentologists and stratigraphers place considerable importance on primary depositional structures for interpreting paleoenvironments (Winston and Anderson, 1971). Yet it is known that wherever the numbers of benthic organisms are high, and where the sedimentation rate is slow, secondary bioturbate structures produced by the organisms may dominate (Warme, 1965; Reineck, 1967). Even though organisms play an important role in producing and altering the composition, texture, and structures of sediments, relatively few studies have been conducted on the biogenic activity in recent, temperate subtidal environments.

Preliminary investigations on the ecology of Axius serratus include: regional distribution, spatial distribution, and burrow morphology. Additional work on biotic associates and general taxonomy was also conducted.

In a classic paper, Weimer and Hoyt (1964) studied the relationship between the thalassinid Callianassa major and the ichnogenus Ophiomorpha. Taken in its usual sedimentary framework, Ophiomorpha has proven to be a valuable shoreline indicator. Ophiomorpha, however, has recently been found in Cretaceous flysch in California, which raises the possibility that other crustaceans make *Ophiomorpha*-like burrows (Kern and Warme, 1974). Resin casts of *Axius* burrows display features similar to *Ophiomorpha*.

Previous investigators have demonstrated how organisms increase sediment water content (Chapman, 1949; Harrison and Waas, 1965; Rhoads, 1970, 1974). In the Strait of Canso, the distribution of mass physical properties were analyzed in conjunction with the proximity of *Axius* burrows.

B. Physical Setting: The Strait of Canso

The Strait of Canso (Figure 1-1) separates Cape Breton Island and mainland Nova Scotia. The Strait varies from 0.8 to 2 km. wide and is 27 km. long with a maximum depth of 60 m. (in the central channel). In 1954 a causeway was constructed across the Strait from Auld's Cove to Port Hastings. This causeway bisects the Strait and exerts strong influences on both the oceanographic and sedimentary environments.

1. The Oceanographic Environment

Prior to the construction of the causeway, the Strait of Canso served as a connection between the Gulf of St. Lawrence and the Atlantic Ocean, through St. Georges Bay and Chedabucto Bay. The tidal interaction in the Strait, caused by the slightly higher tidal range of the Atlantic Ocean

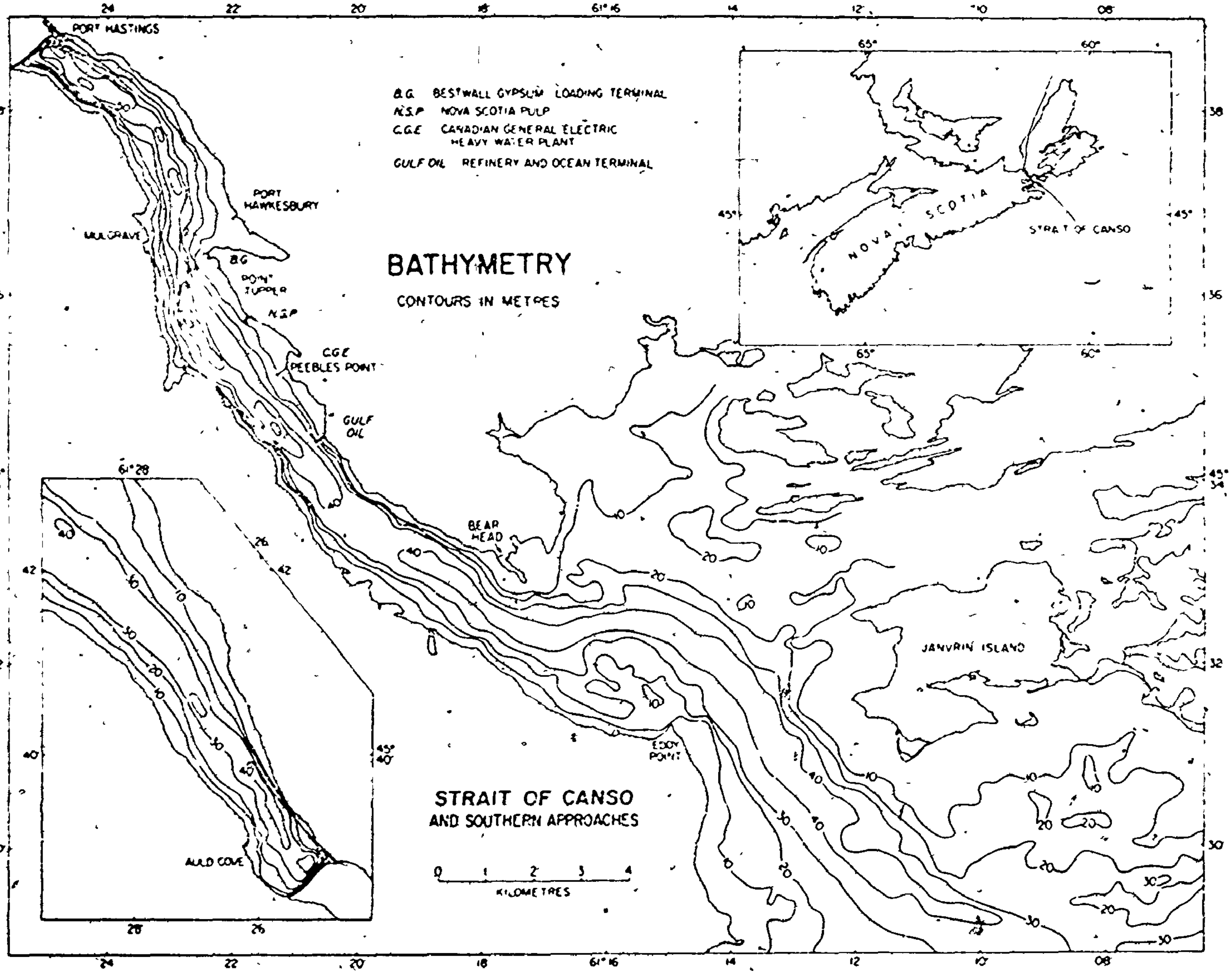


Fig. 1.1: Location of study area; Strait of Canso.

(Fothergill, 1955), created a gentle downward slope of the mean sea-level surface from St. Georges Bay to the Atlantic Ocean. This slope resulted in a net water flow southward of 3.68×10^8 m^3/day (Fothergill, 1955), which has a southward current averaging 9.6 km/hr, against a northward current averaging 7.9 km/hr (Fothergill, 1954). In winter, the net tidal currents transported ice from the Gulf of St. Lawrence through the Strait and into Chedabucto Bay. This resulted in the Strait being filled with jam ice all winter.

Since the advent of the construction of the causeway the Strait of Canso is divided into northern and southern sections. This bisection has had a profound affect on the circulation patterns, the strong tidal currents disappeared and circulation is now influenced by meteorological conditions. Wind generated currents are now the dominant driving force on water circulation (Lawrence _et al_., 1973). The strong bottom currents in the Strait, prior to the causeway's construction have been greatly reduced, on the south side of the causeway a relatively weak current of 1.85 km/hr now exists (Buckley _et al_., 1974).

The causeway, as well as preventing local water mixing, and reducing currents, also acts as a dam to flow ice in winter. Thus an ice-free deep water port was inadvertently created on the southern side of the causeway. Small communities along the Strait grew rapidly and the urban population swelled from 2,872 to 5,700. Four major industries have been established in the area since 1954. The Georgia Gypsum Co. began operation at Point Tupper in the latter part of the 1950's; the Nova Scotia Forest Industries established a pulp and paper mill in the early 1960's; the Canadian General Electric heavy water plant in 1970, and the Gulf Oil refinery in 1971.

2. The Sedimentary Environment

Prior to and during the construction of the causeway, the deposition of fine sediment could not have taken place due to the strong currents. When the causeway was half completed currents in the area underwent large-scale changes. A south-going current of 12.8 km/hr resulted in nondeposition and scouring of bottom sediments. After the completion of the causeway, the resulting weaker currents permitted a significant increase in the deposition of fine-grained sediments (Buckley _et al._, 1974).

In an attempt to estimate the sedimentary deposition rate, Buckley _et al._ (1974) used polynological techniques. The first appearance of pollen of the weed _Rumex acetocella_, which was first introduced by European settlers in approximately 1750, was used as a datum. The rate of sedimentation was determined from the average depth of this boundary in the sediment column. A rate of 7.8 to 18.1 cm. per 100 years for the top 15 to 45 cm. was determined for sediments on the north side of the causeway. A rate of 9.0 to 14.6 cm. per

100 years for the top 5 to 35 cm. was determined for sediment on the south side of the causeway. From this rate, Buckley et al. (1974) estimated that since construction of the causeway, 1.6 to 3.8 cm. was deposited on the north side, and 1.8 to 2.9 cm. on the south side.

The recognition of the layer of sediment deposited since completion of the causeway is complicated by the activity of benthic organisms, which obliterate any sharp discontinuities in the sediment (Vilks et al., 1975). In a study of benthic foraminifera in the Strait of Canso, Vilks et al. (1975) observed that bioturbation mixed sediment across time boundaries, making the resolution of closely-spaced events in the sedimentary history of the area extremely difficult.

3. The Study Area

Major sampling locations were located in the relatively shallow water harbours situated adjacent to the towns of Port Hawkesbury (Ship Harbour) and Mulgrave (Pirate Harbour) (Figure 1-2), on the south side of the causeway. The salinity and temperature of the water profile during the summer range from 28.5 to 31.5 parts per thousand, and from 17 to 3 degrees celsius (Buckley et al., 1974). The predominant sediments are locally-derived glacial tills. These closely reflect the nature of the underlying bedrock, which consists of interbedded Carboniferous sedimentary rocks, including

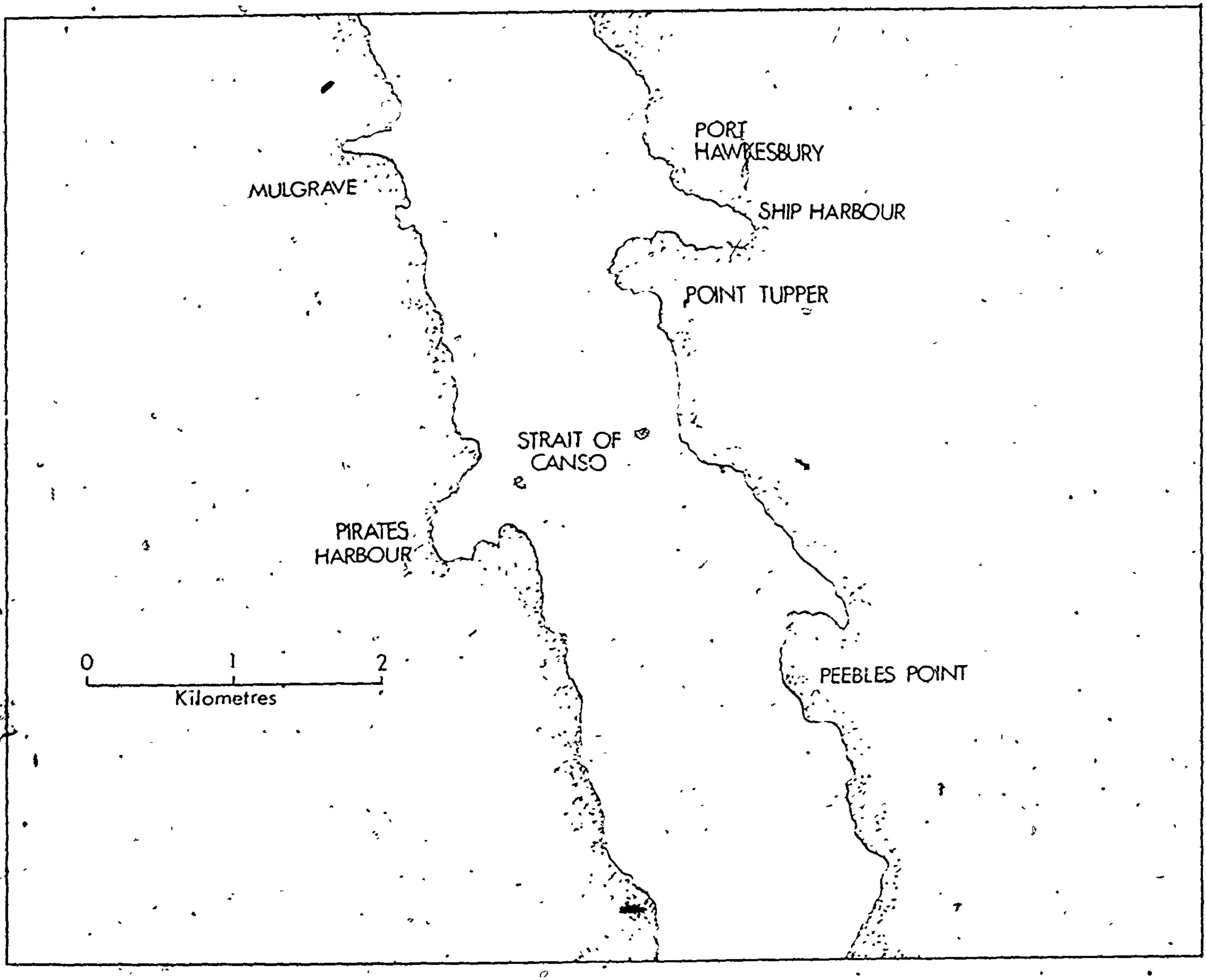


Fig. 1.2: Location of Ship Harbour and Pirate Harbour.

shale, sandstone, limestone, and conglomerate (Brown and Rashid, 1975). The bottom is underlain by similar tills, a result of a rise in sea-level plus submergence of the land following the last glaciation. Sediments of these shallow harbours are usually silts and clays (Buckley et al., 1974).

As a result of the large industrial growth previously discussed, great amounts of effluents are discharged into the saline waters of the Strait. During the summer months there is a natural stratification in temperature and salinity (Figure 1-3). The warmest and least saline layers in the upper 15 m. are moved horizontally, predominantly by winds. Below 15 m. the waters are relatively cold and are moved under the influence of tides (Lawrence et al., 1973). Thus, a water circulation pattern is established similar to that of a two-layer estuary, with the upper layers containing more fresh water and receiving most of the land drainage and effluents (Buckley et al., 1974). Analysis of the current data presented by Lawrence et al. (1973) shows that in the Strait of Canso the currents are strongly confined in direction, to the axis of the Strait. The upper layer has velocities generally less than 0.3 knots, with a preferred flow direction being inward (northwesterly) towards the causeway. The lower layer has velocities generally less than 0.2 knots, showing an outward flow (toward Chedabucto Bay).

Analysis of the distribution of trace metals,

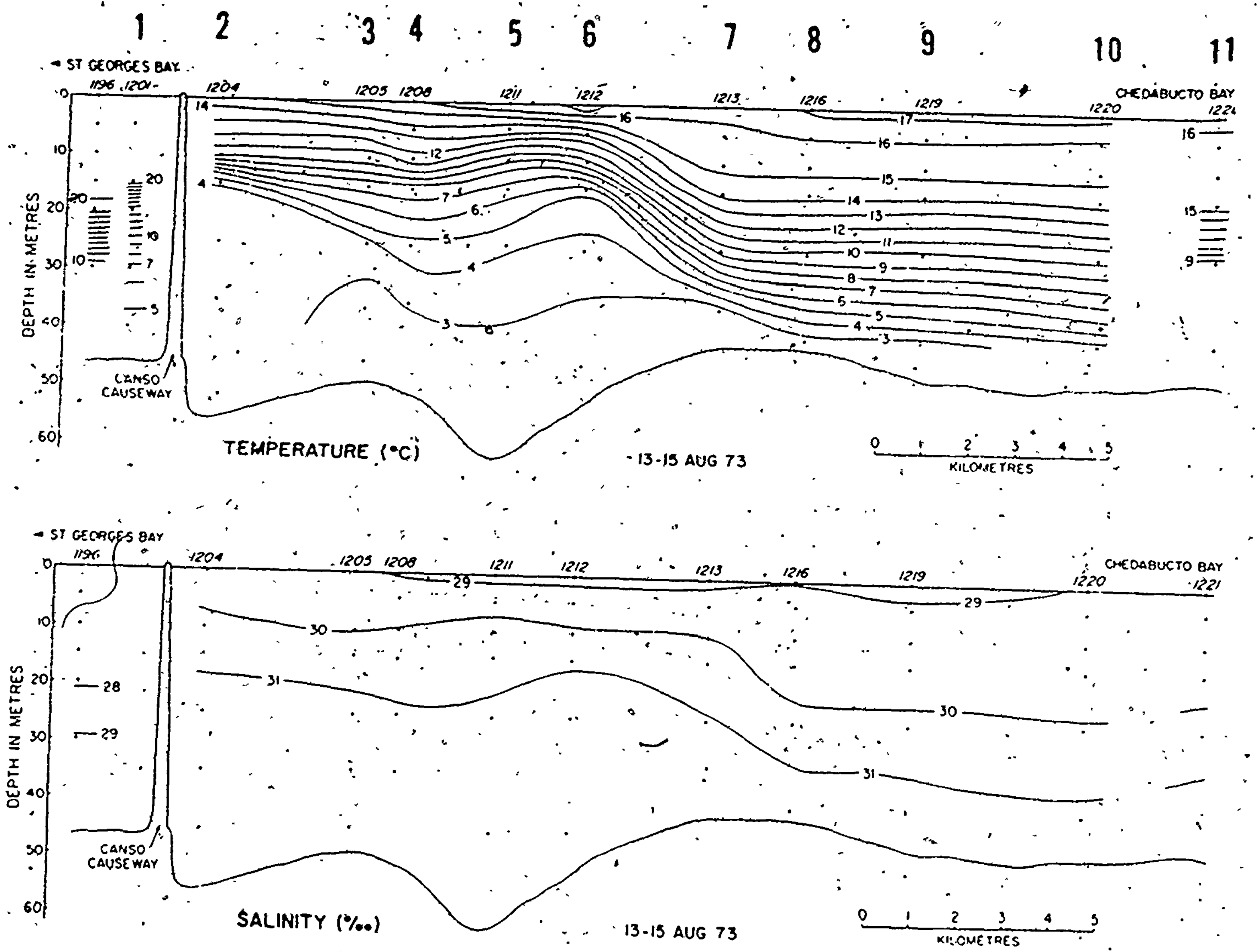


Fig. I-3: Axial profile of temperature and salinity during August in the Strait of Canso (after Buckley, et al., 1974).

bacteria, and water turbidity conducted by Buckley et al. (1974) and Cranston et al. (1974) indicate a consistent decrease in concentration with increasing distance from the industrial complex centred at Point Tupper. The two major study areas, Ship Harbour and Pirate Harbour, are located adjacent to heavy industrial outfall and are subject to heavy pollution. Buckley et al. (1974) point out that the surface layer contains higher concentrations of all effluents measured, while bottom waters (deeper than 15 m.) are rather homogeneous and are only slightly affected by the quality of the surface layer. Since both Ship Harbour and Pirate Harbour are relatively shallow (12 m. maximum depth) they are both subjected to surface waters containing the bulk of the industrial effluents, which are brought in by the predominantly inward moving surface current.

CHAPTER TWO

UNDERWATER METHODOLOGY

A. Polyester Resin Casting

The use of polyester resin casts in the study of burrowing organisms was first introduced by Shinn (1968), and extensive use of the method has since been reported (Frey and Howard, 1969; Farrow, 1971; Frey *et al.*, 1973; Karplus *et al.*, 1974). The technique has been restricted mainly to intertidal areas but some studies employ the method in subtidal depths (Rice and Chapman, 1971; Atkinson, 1974).

In a recent study of the burrowing activities of the Norway lobster (*Nephrops norvegicus*) Rice and Chapman (1971) employed Shinn's method. Prior to casting, the catalyst was mixed with the resin ashore and the accelerator added immediately before diving; the mixed resin was then carried to the bottom in open-topped containers and poured into selected burrows (Rice and Chapman, 1971).

An improved casting method has been developed which calls for the addition of the catalyst hardener directly before pouring on the bottom. This method has been successfully used in the fine muds of the Strait of Canso and in coarse, often poorly-sorted sands off the coast of southern California. The polyester resin is poured into a 6 ml. plastic bag. The hardener is placed in a plastic vial equipped with a snap lid. For smaller amounts of resin, large gelatin capsules may be used. The bag, with the resin and hardener in it, is then fitted with a length of rubber hose (Figure 2-1). All air is then extracted from the bag and a cork is fitted into the hose in order to prevent water leakage. The bag is then taken to the bottom by SCUBA divers. After a suitable burrow is located, the hardener is mixed with the resin by forcing open the plastic vial. The cork is extracted and the hose is inserted into the burrow (hose size is variable with the size of the burrow opening), and the resin is poured (Plate 2-1).

This modification of Shinn's method allows the operator some time to choose the burrow he wishes to cast, and resin bags may even be stored for several days without damage. After a while, however, catalyst slowly leaks out of the container, causing the container to become surrounded with an impenetrable shield of catalyzed resin. Complete enclosure by a plastic bag also ensures no damage to SCUBA equipment by resin leakage. It was found that twice the normal amount of hardener provided the best results in the fine sediments of the Strait. After twenty-four hours, recovery of the case was made with the use of the suction dredge.

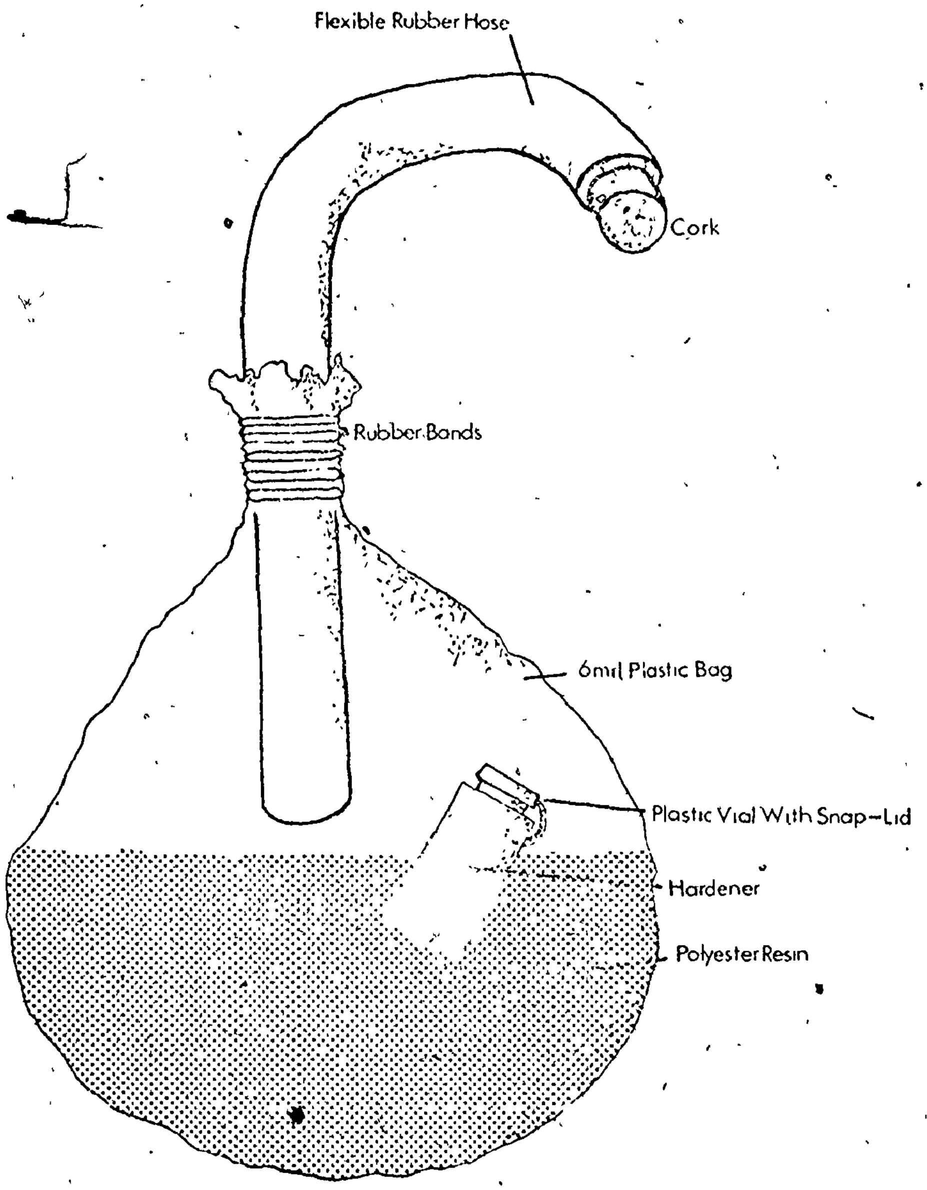


Fig 2.1: Apparatus used for pouring resin

Plate 2.1: Diver pouring resin down shrimp hole.

B. Portable Hydraulic Diver-Operated Suction Dredge

A portable diver-operated suction dredge was reported by Brett (1964), and since modified by Ekdale and Warme (1972). The unit used in this study (Figure 2-2) has been modified from Brett's description, to adapt to the particular environment of the Strait of Canso. The general advantages and disadvantages of suction dredges of this type have been outlined by Brett (1964), and True *et al*. (1968).

A three horsepower Briggs and Stratton gasoline engine powers a Monarch self-priming centrifugal pump. This pump is capable of discharging 504 litres of water per minute with a vertical lift of up to 7.5 m. Water is taken into the pump by a neoprene hose (5.4 cm. I.D.) fitted with an aluminium strainer (to ensure that no pelagic fauna and flora are sucked into the pump). This water is then discharged down a 15 m. neoprene hose (5.4 cm. I.D.), coupled to the dredge unit by use of a copper gate valve. This valve can then be used to regulate the flow of water (and hence the suction) into the dredge unit.

The dredge unit (Figure 2-3) is comprised of a 2.4 m. P.V.C. (Schedule 40) pipe (10.2 cm. I.D.), attached to the copper gate valve by a 30 cm. length of flexible rubber hose (5.4 cm. I.D.). The water is pumped into the dredge unit (60 cm. from the operator's end) and up the P.V.C. pipe by use of a 90 degree elbow joint (P.V.C. pipe, 4.6 cm. I.D.),

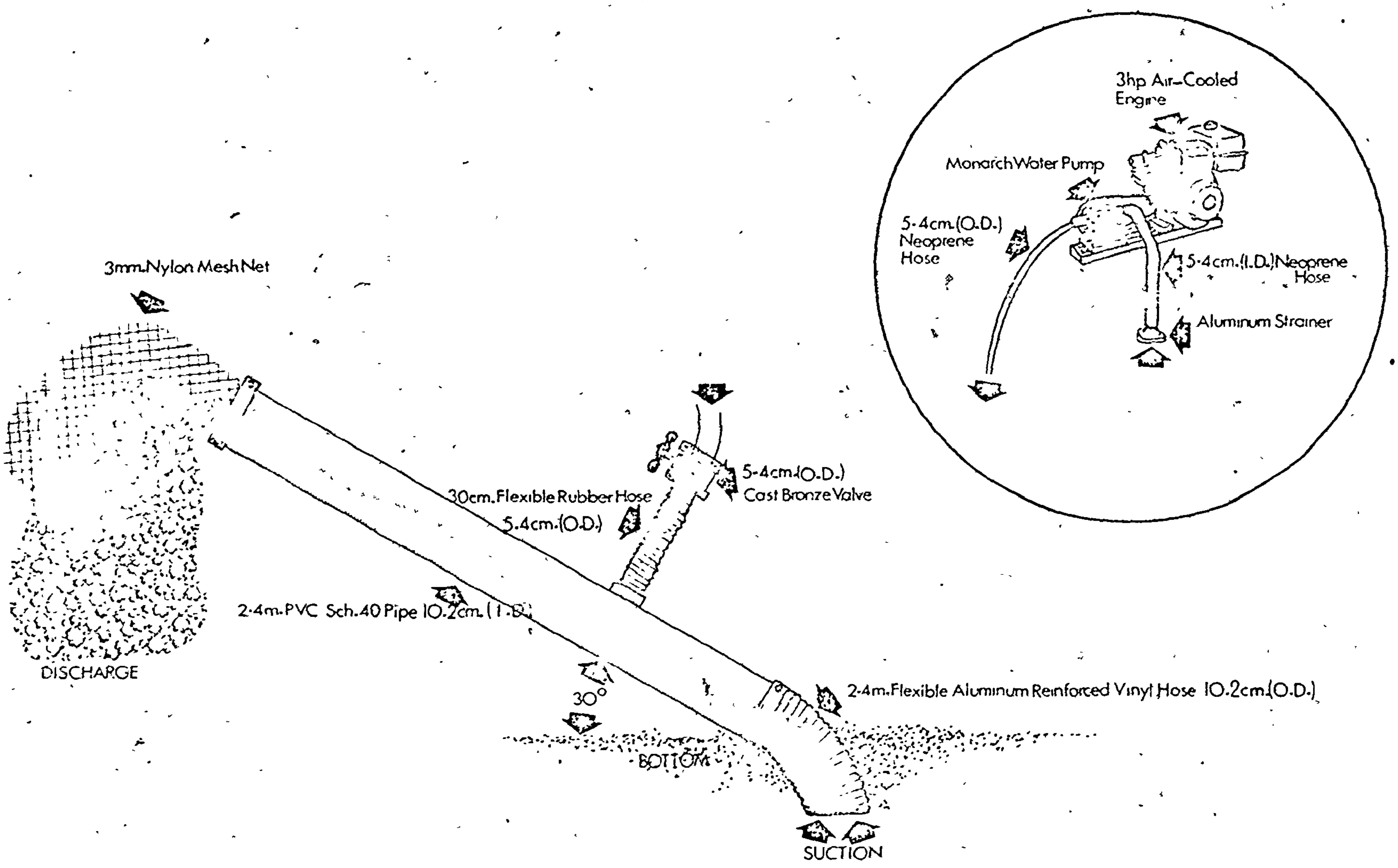


Fig. 2-2: Portable Hydraulic, Diver-operated Suction Dredge (modified from Brett, 1964)

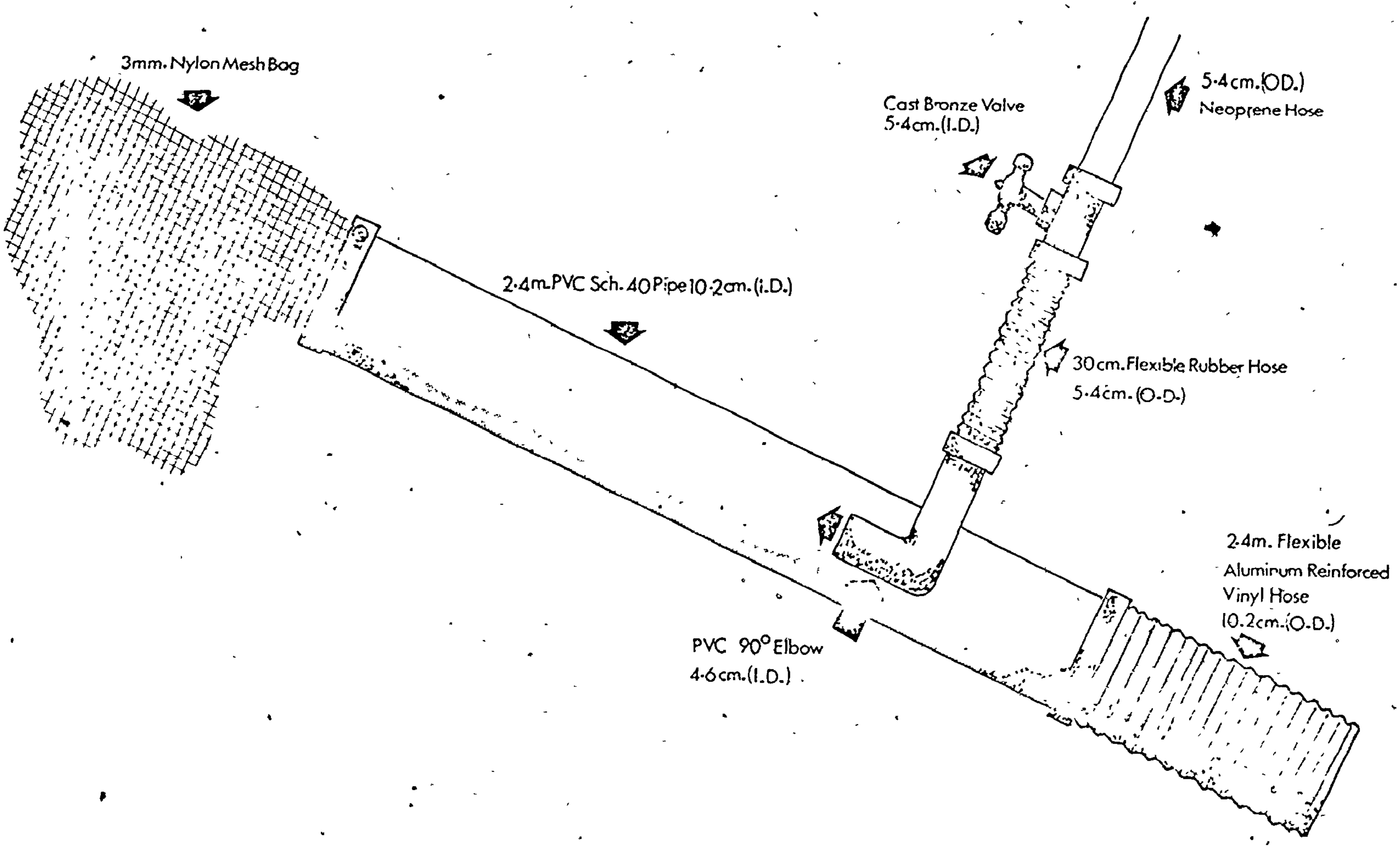


Fig. 2-3: The suction unit.

This creates the suction at the operator's end, where a 2.4 m. flexible vinyl (aluminium reinforced) hose (5.4 cm. O.D.) is used to excavate the burrows. At the distal end of the 2.4 m. P.V.C. pipe is a nylon netting bag (3 mm. mesh) attached with a worm gear hose clamp.

The dredge unit is operated by two SCUBA divers. One diver operates the unit while the other man acts as a diver safety man and assists in moving the unit from one area to another. The unit can easily be operated from a small skiff and affords a sweeping range limited only by the length of the water discharge hose from the pump. Since the unit was employed in extremely soft sediment, with normal visibility of from 1 to 8 feet, it was found that holding the 2.4 m. P.V.C. pipe at a 30 degree angle to the sediment-water interface reduced clouding effects due to stirring of the bottom. This angle of course is dependent on the type of bottom sediment that is being sampled.

Polyester resin casts extending 3 m. into the sediment were recovered using the dredge unit with no operational difficulties (Plate 2-2). The time of excavation was usually minimal, due to the fine muddy sediment. In addition, the dredge was also used to capture deep burrowing organisms. With the addition of long handles (1.5 m. in length) it was possible to excavate and capture organisms that may occupy burrows several meters deep.

Plate 2.2: Cast of shrimp burrow from Ship Harbour.

With slight modification the suction dredge can be changed into a water injection system. The dredge unit (Figure 2-3) is removed and a 1 m. length of copper pipe (1.5 cm. I.D.) is connected by means of reducers to the cast copper gate valve (Figure 2-4). The water injection system has been used in the capture of deep burrowing organisms (W. Pryor, personal communication). Water is injected down the burrow openings, which flushes their occupants out. In the present study inter-connections between burrow openings were determined by squirting a potassium permanganate solution into a burrow entrance from a wash-bottle and noting from which holes the solution escaped. Once the burrow complex (main burrow opening plus any auxiliary openings) was determined, fine mesh nylon nets were placed over all the burrow openings in the surrounding area and water injected into the main burrow entrance by means of the copper pipe. Any organisms that were flushed out were captured in the nylon mesh. The copper gate valve proved useful in regulating the strength of the water jet. It should be noted that no shrimps were captured using this technique.

C. Sediment Cores

The can core is an inexpensive and simple tool, for the study of the effects of bioturbation on the sediment-water interface. The can core consists of a standard,

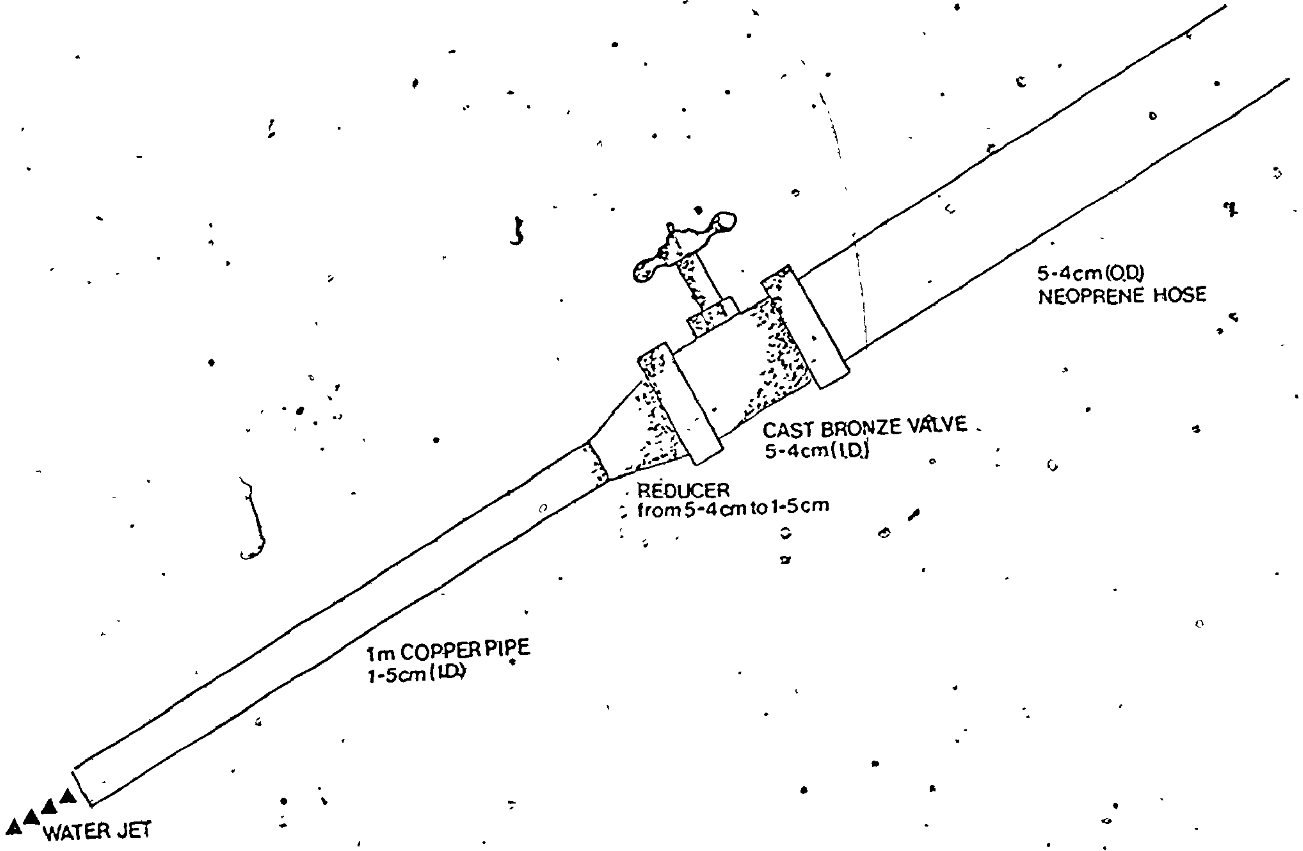


Fig. 2-4:. The injection unit

rectangular, gallon can (Vulcan Containers, Rexdale, Ontario) with the bottom removed (Howard and Reineck, 1972). The core is taken by removing the screw cap and inserting the can into the sediment. A small hand trowel is used to dig the can ~~out.~~ A piece of styrofoam is inserted under the can and forced onto the bottom of the can. A length of rubber hose is used as a rubber band to ensure that the styrofoam adheres to the can. This is done to minimize the amount of sediment lost in transport.

It is imperative that one takes care to ensure that the core is not disturbed. In working with excessively bioturbated sediment of fine-grain size, extra caution is advised. The bioturbation process increases the thixotropic liquifaction of the sediment-water interface (Rhoads, 1970). Thus, it is important that one not hammer or vibrate the core when pushing it in, since this only increases the thixotropic liquifaction of the sediment and textural rearrangement can occur (Rosefelder and Marshall, 1967). Disturbance of the sediment upon withdrawal can occur because of several factors: decrease of hydrostatic pressure below the sample; adhesion of the sample and the subsoil; lack of wall friction and adhesion between the sample and the core wall (Rosefelder and Marshall, 1967).

These can cores can now be dried and cut longitudinally, to be examined by X-ray radiography (Howard, 1968).

Since the can core is rectangular, the edges will not be over-exposed as they would in a circular one.

CHAPTER THREE

AXIUS SERRATUS

A. Taxonomy

The species Axius serratus (Figure 3-1) is a little known mud shrimp of the order Thalassinidea. The species has previously been reported from the northeastern coast of the United States by Stimpson (1852) and Smith (1879). Prior to this study, the only Canadian record (Rathbun, 1929) is from the Bay of Fundy. The European species which most closely resembles A. serratus, Axius stirhynchus (Smith, 1879), has been reported from the Irish coast, the south coast of England, the Channel Islands, the Bay of Biscaye, and the Mediterranean Sea (Borradaile, 1903; Selbie, 1914).

The order Thalassinidea are a group of burrowing decapods that exhibit compact, elongated bodies. Their clawed limbs have strong palmae, and the dactyli of the limbs are made for digging. The other pereipods are wide and set with bristles and are used to create currents which aid in respiration while the animal inhabits its burrow (MacGintie, 1934). Thalassinids build large burrow systems in sandy-mud and mud bottoms. The order is divided into four families: Axiide, Laomediidae, Thalassinidae, and

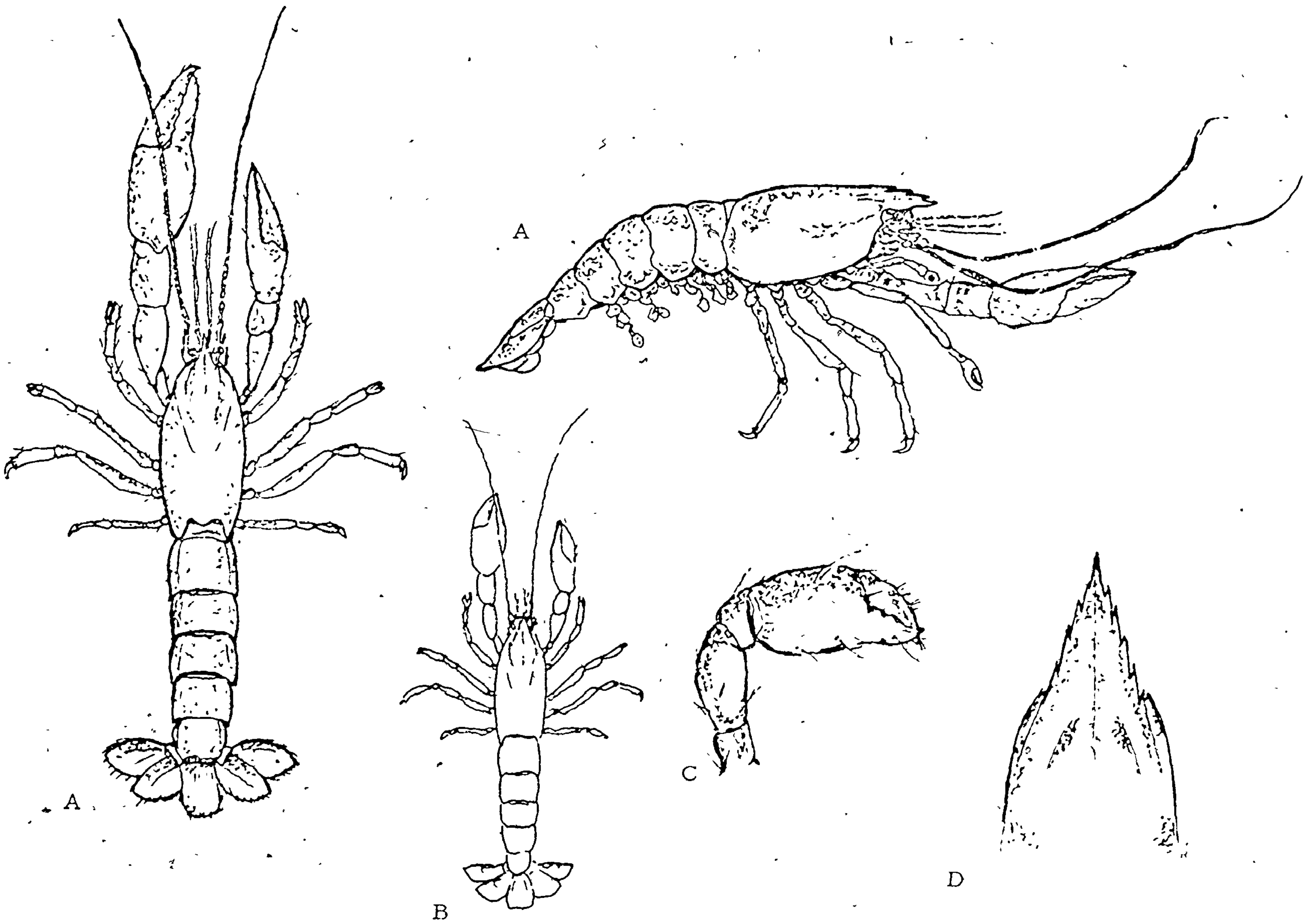
Fig. 3-1:

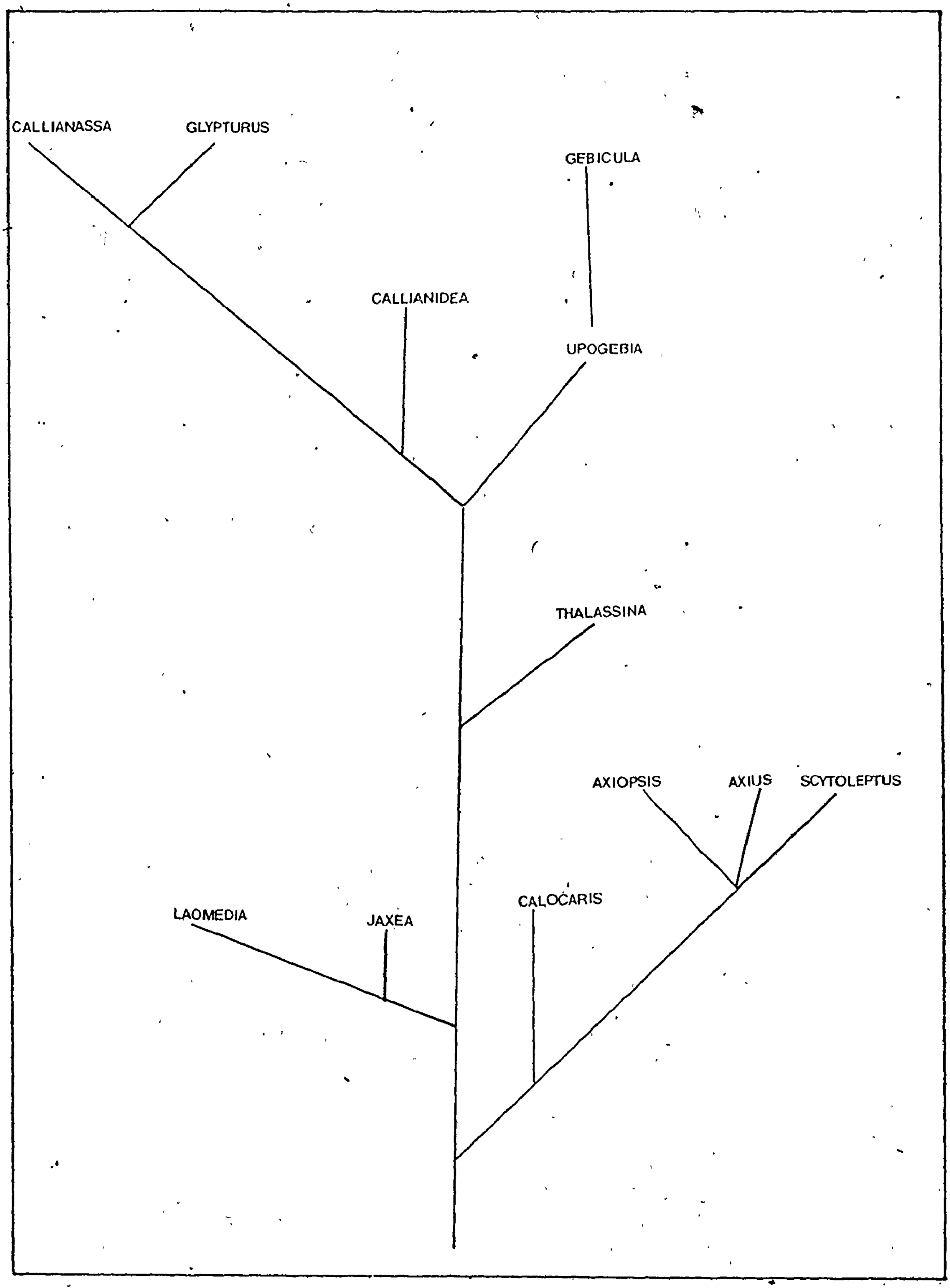
A. Adult specimen of *Axius serratus*, from the Strait of Canso, (X 1/2)

B. Juvenile specimen of *Axius serratus* from Pirate Harbour (X 1)

C. Large chelae of adult specimen (X 5)

D. Serrated rostrum of adult specimen (X 20)


A
A
B
C
D


CALLIANASSA
GLYPTURUS
GEBICULA
CALLIANIDEA
UPOGEBIA
THALASSINA
AXIOPSIS
AXIUS
SCYTOLEPTUS
LAOMEDIA
JAXEA
CALOCARIS

[illegible] 3-2. [illegible]

Table 3-1: Key to the Families of the Thalassinidea (after Borradaile, 1903)

I. No *linea thalassinica*. Both movable and fixed antennal thorns present, though sometimes minute (? absent in *Scytoleptus*). Abdominal pleura large .... Axiidae.

II. *Linea thalassinica* present (except in *Callianassidae*) Fixed antennal thorn wanting, scale reduced to a flattened vestige or wanting. Abdominal pleura usually small.

  1. Sutures on both exopodite and endopodite of last limb. Abdominal pleura of a good size...................... Laomediidae

  2. No sutures on the last limb. Abdominal pleura small.
     a. Second leg chelate or simple. No podobranchs on legs. Abdominal limbs 3-6 broad. A vestige of antennal scale remains............................ Callianassidae
     b. Second leg subchelate. Podobranchs on legs 1-3. Abdominal limbs all narrow. No vestige of antennal scale........................ Thalassinidae

Key to the Genera of the Axiidae

I. A suture on the exopodite of the last limb. (Antennal thorns present, large or small)

  1. Eyes pigmented. Back flat. No keel in the hinder part of the carapace at least................. *Axiopsis*.

  2. Eyes pale. Back arched. A keel runs the whole length of the carapace in the middle line....... *Calocaris*.

II. No suture on the exopodite of the last limb.

  1. Back not falling steelply to rostrum. Antennal thorns present, large or small.............. *Axius*

  2. Back falling steeply to *rostrum* Antennal thorns lost (?) .... *Scytoleptus*

Key to the Subgenera of Axius

I. Eyes pigmented. Flat area of back and cervical groove well marked. (Antennal thorns large)

1. Pleurobranchs on legs 2-4. . . . . *Axius*

2. No pleurobranchs . . . . *Neaxius*

II. Eyes pale. Flat area of back and cervical grove more or less indistinct.

1. Pleurobranchs on legs 2-4, Antennal thorns large.

   a. Gills on second maxilliped . . . . *Iconaxiopsis*
   b. No gills on second maxilliped. *Eiconaxius*

2. No pleurabranchs, Antennal thorns small . . . . *Paraxius*

Callianassidae; and twelve genera. The genealogical relations between the genera of Thalassinidea is given in Figure 3-2. The characters and subdivisions of the four families are set forth in key form in Table 3-1.

1. Family: Axiidae BATE, 1888

Members of the family Axiidae possess a large size rostrum without the groove or crack which runs lengthwise on each side of the cephalothoracic carapace (linea thalassiniea), which is typical of most families of thalassinids. Long antennular flagella, with an antennal seale present as a movable thorn-like structure situated between the second and third joints of the antennal stalk. An immovable thorn is situated outside the seale on the second joint.

The first pair of legs are large unequal chelate; the second pair ending in small equal chelate; the third to fifth pairs are simple with the fifth pair sometimes tending to be subchelate. There are no gills on the first maxilliped, but mastigobranchs are present on legs one to four and podobranchs on legs one to three. The gills are trichobranch with narrow filaments. The pleura of the abdominal segments are well- or moderately well-developed. The five pair of abdominal limbs possess appendix interna whose branches vary from narrow to fairly broad. The last pair of limbs have the endopodite unjointed and the exopodite with or without joints.

Borradaile (1903) recognizes four different genera in this family: Axius, Axiopsis, Calocaris, and Scytolcptus.

2. Genus: Axius LEACH, 1815

Axiidae in which the body is more or less compressed from side to side in front of the cervical groove, so that the back in this region displays a platform. This platform may be either flat or convex, and is often marked at its edges and along the middle line by ridges. With or without pleurobranchs, and with no suture on the expodite of the last abdominal limb.

Borradaile (1903) recognizes five different subgenera in this genus: Axius, Neaxius, Iconaxiopsis, Eiconaxius, and Paraxius.

3. Subgenus: Axius LEACH, 1815

Species of Axius with the flat area of the back and the cervical groove well marked and the eyes are well pigmented. The antennal thorns are both large and pleurobranches are present on the second to fifth legs. There are vestiges of a podobranch and an arthrobranch on the second maxilliped.

4. Species: Axius serratus STIMPSON, 1852 (Figure 3-1)

The following description is after Stimpson (1852) and the present study. The carapace is smooth and much compressed with few scattered hairs. The transverse suture is prominent and quite deep. The rostrum is small and elongated with the medial carinae sharp, and the lateral ones are serrated with seven teeth on each. The carinae are continued for a short distance onto the carapace where they are simple, less prominent and are diverging. Interior antennae are as long as the carapace. The exterior antennae have a long peduncle; the basal joint is compressed and concave with a small spine. The external maxillipedes are long and slender with a small spine at the end of the third joint. The feet are much compressed and hairy on their edges, the anterior pair with minute spines along the lower edges of the second and third joints. Chelae with very long hairs; thumb strongly dentate on its inner margin; finger with shallow grooves and serrated within, in left chelae but not in right chelae. Didactyle extremities of second pair of feet are compressed, short, broad and ovate; monodactyle extremities of the remaining feet are actually short hairs.

The abdomen is approximately one and two thirds the length of the carapace. It is broad with the segments terminating bluntly below. The caudal segment has a single minute spine on each side of the medial furrow. The lateral caudal plates each have a small spine at its inseration with the abdomen, the interior spine with one longitudinal ridge and the external spine with two longitudinal ridges.

5. World-Wide Distribution of Axius serratus

The specimen that was described by Stimpson (1852) was obtained in a dredge sample from Massachusetts Bay at a depth of 60 m. Smith (1879) records a partially digested specimen found in the stomach of a flounder (Glyptocephalus cynoglossus), which was taken in Massachusetts Bay at a depth of 85m. An additional specimen is recorded from the Bay of Fundy, but no further details are known about its location, (Rathbun, 1929).

B. Regional Distribution

Investigation of Axius serratus revealed that the shrimp, once thought to be extremely rare, is found in abundance off the east coast. In the Strait of Canso region, numerous dives indicate that Axius is restricted to the area south of the causeway. No burrows were encountered on the north side of the causeway. Axius burrows were observed in all localities studied from the causeway south to Chedabucto Bay. The shrimp was encountered in all depths ranging from 5 to 35 m. (the deepest dives made).

Previous studies conducted in the Strait by Buckley et al. (1974), Vilks et al. (1975), and Wagner (1975) revealed that two distinct invertebrate "barren zones" existed along the northeastern coast (Figure 3-3). One is located in the far end of Ship Harbour, and the other is adjacent to the

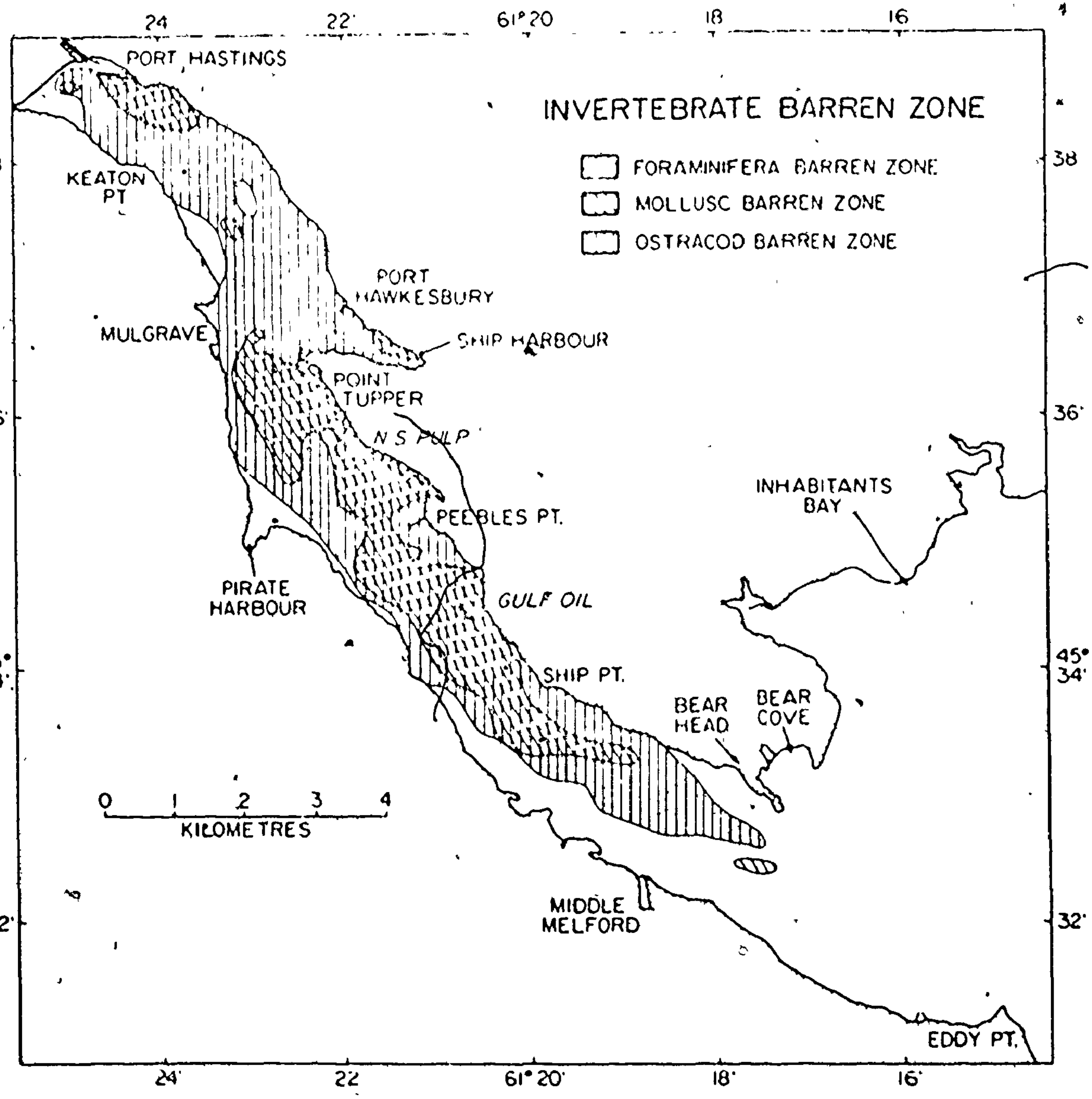


Fig. 3-3: Invertebrate barren zones in the Strait of Canso, (after, Buckley et al., 1974).

Nova Scotia Pulp Mill. Both these areas are devoid of molluscs, foraminifera, and ostracods. Diving in these barren zones revealed that Axius burrows were present in densities of from 7 to 9 per square meter. No other macro-invertebrate life was encountered. The presence of Axius serratus in these zones indicates that the shrimp is able to withstand and thrive in highly polluted areas which are not successfully exploited by other organisms.

In 1969 and 1973, the Bedford Institute of Oceanography conducted cruises along the Scotian Shelf and Chedabucto Bay, for the purpose of obtaining bottom photographs of these two areas. Subsequent study of these pictures revealed that characteristic Axius burrows were present. These burrows are similar in size and geometry to the burrows found in the shallower water of the Strait of Canso. The 1969 cruise of the Scotian Shelf photographed eleven stations that displayed these burrows (Figure 3-4). Seven stations in Chedabucto Bay (Table 3-2) also displayed a number of burrows that are thought to be similar to the ones created by Axius.

In summary, Axius burrows were not only encountered in all parts of the Strait of Canso south of the causeway, including the barren zone, but also throughout Chedabucto Bay and the Scotian Shelf.

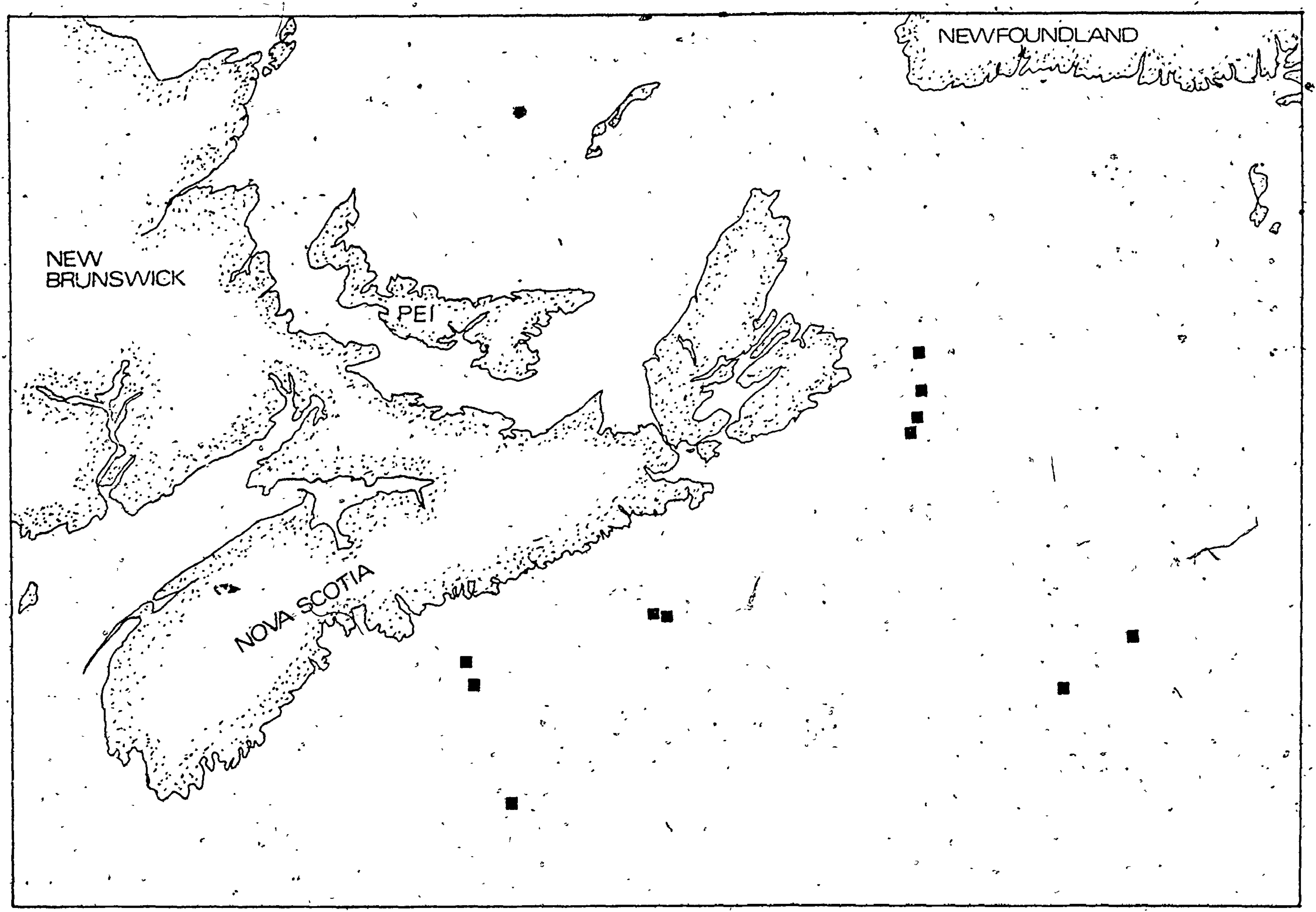


Fig. 3-4: Stations displaying Axius-like burrows on the Scotia shelf.

Table 3-2: Location of stations in Chedabucto Bay which display *Axius*-like burrows.

Station Number	Latitude	Longitude	Water Depth (m)
1	45-37.10N	61-21.90W	52
20	45-29.80N	61-11.50W	42
47	45-22.25N	61-23.7W	31
70	45-22.0N	61-03.7W	88
100	40-28.9N	60-44.3W	129
117	45-25.0N	60-39.2W	160
131	45-22.5N	60-31.4W	117

C. Spatial Distribution

Spatial pattern is one of the most important characteristics of any population of living organisms (Connell, 1963). Preliminary studies on the spatial distribution of organisms were first introduced by plant ecologists (see Greig-Smith, 1975, for review). These techniques have been applied to animal populations (Salt and Hollick, 1946; Holme, 1950). From these studies it has been shown that, although spatial distribution can be extremely variable in any locality, few populations are completely random. Three main types of distribution have been recognized: uniform, aggregated and random.

A non-random dispersion pattern implies that some sort of constraint is being placed on the population. Aggregation is thought to be caused by gregarious behaviour, reproductive habits or heterogeneity of the environment, such that individuals are clumped in the favourable parts of the habitat (Connell, 1963). A uniform pattern results from some type of negative interaction between the individuals (Holme, 1950), such as competition for food supply (as illustrated in deposit feeding populations).

In the analysis of the spatial distribution of _Axius serratus_, in the Strait of Canso, two independent techniques were used: the distance to the nearest neighbour (Clark and Evans, 1954), and the coefficient of dispersion (Clapham, 1936). An attempt was also made to discern social pressures and the effect of discontinuities in the substrate.

1. The Distance to the Nearest Neighbour

The technique of using the distance to the nearest neighbour in analyzing the dispersion of an individual population was first introduced by Hertz (1909). Subsequent development of the technique was by Spooner, quoted in Holme (1950). Dice (1952) was the first to use distance to nearest neighbour in measuring departure from randomness. The technique was further refined by Clark and Evans (1954, 1955) and Clark (1955). The technique of distance to nearest neighbour has been used effectively in the analysis of populations of the bivalves *Mya* and *Petricola* (Connell, 1956); *Tellina* (Holme, 1950); and the amphipod *Erichthonius braziliensis* (Connell, 1963).

This measure of spacing is a measure of the degree with which the distribution of individuals in a population departs from that of a random distribution (Clark and Evans, 1954). In the Strait of Canso, measurements were obtained in two sub-areas, Ship Harbour and Pirate Harbour. Random areas were chosen within these harbours by throwing buoys overboard, which were then used as centres of quadrats. Roped quadrats 2 m. by 2 m. were stretched over the bottom, all burrows were charted and the distance to the nearest neighbour recorded. Care was taken to discern between burrow openings, since one main burrow hole may be associated with up to three auxiliary holes. The relationship between main openings and auxiliary openings was established by squirting a potassium permanganate solution down the main opening and observing from which holes the dye is expelled. This dye irritates the shrimp and is actively pumped out of the burrow.

The equations used (Table 3-3) and the procedure outlined below is summarized from Clark and Evans (1954).

In a population with N individuals and a density (p), the distance (r) from each individual to its nearest neighbour is measured. The mean observed distribution is given by:

$$\bar{r}_A = \Sigma r/N$$

and the mean distribution expected if the population is a random one is given by:

$$\bar{r}_E = 1/2 \sqrt{p}$$

The ratio $\bar{r}_A/\bar{r}_E$ (R), is then used as a measure of the departure from the random expectation. In a random distribution R will equal unity; under conditions of aggregation R will approach zero; and under conditions of maximum spacing R will be greater than unity (Clark and Evans, 1954). The test of significance of the measure is given by:

Table 3-3: A list of symbols and definitions of concepts, employed in a measure of spacing based on the mean distance between the nearest neighbour.

N:	number of measurements
r:	distance to nearest neighbour
p:	density per unit area
r:	summation of the measurements of distance to nearest neighbour
r^2:	summation of squares of the measurements of distance to nearest neighbour
$\bar{r}_A = r/N$:	the means of the series of distance to the nearest neighbour
$\bar{r}_E = 1/2\ p$:	mean distance to nearest neighbour expected in an infinitely large random distribution of density p
$R = \bar{r}_A/\bar{r}_E$:	the measure of the degree to which the observed distribution departs from random expectation with respect to the distance to nearest neighbour
$c = \frac{\bar{r}_A - \bar{r}_E}{\theta_{F_E}}$:	standard variate of the normal curve
$\sigma_{\bar{r}_E} = 0.26136/_{Np}$:	the standard error of the mean distance to nearest neighbour in a randomly distributed population of density p

$$c = \frac{\bar{r}_A - \bar{r}_E}{\sigma_{\bar{r}_E}}$$

Where c is the standard variate of the normal curve, and $\sigma_{\bar{r}_E}$ is the standard error of the mean distance to the nearest neighbour in a randomly distributed population of the same density as the observed population.

2. The Coefficient of Dispersion

In the analysis of the distribution of organisms over a specific area, many investigators have used Fisher's "coefficient of dispersion". The method was introduced in studies of plant ecology by Clapman (1936) and Blackman (1942), and in terrestrial and marine ecology by Salt and Hollick (1946), Holme (1950), and Barnes and Marshall (1951).

The coefficient of dispersion is given by:

$$\frac{\Sigma(x - \bar{x})^2}{\bar{x}(n - 1)}$$

Where $\Sigma(x - 2)^2$ is the sum of squares of the deviations of individual units (x) from the mean ($\bar{x}$) of all the units (n) comprising the sample.

The coefficient is unity when the population is randomly distributed, less than one if the population is over-dispersed (evenly distributed), and greater than one if it is under-dispersed (aggregated). The significance of the departure from unity is tested by:

$$1 \pm 2\sqrt{2n/(n-1)}^{2}$$

Where n is the number of units in the sample (Holme, 1950). Where n is less than 10, this latter expression is greater than unity, so that samples numbering less than 10 can not be tested for an even distribution.

In the present study, frames, one square meter in area, were constructed from quarter-inch angle iron. The frame was then thrown overboard "randomly", and the resulting area was then sampled by SCUBA divers. Densities of burrows were recorded in twenty such observations in both Ship Harbour and Pirate Harbour. The presence of occupied burrows was determined, as before.

3. Results

a. Distance to nearest neighbour

The location of all burrow complexes occurring within the roped quadrats from Ship Harbour (Figure 3-5) and Pirate Harbour (Figure 3-6) was determined. Each quadrat was established so that five different measures could be taken, the entire four square meters and four one square meter sections, as determinations of spatial pattern depend somewhat on quadrat size (Evans, 1952). A summary of the results of nearest neighbour analysis is given in Table 3-4.

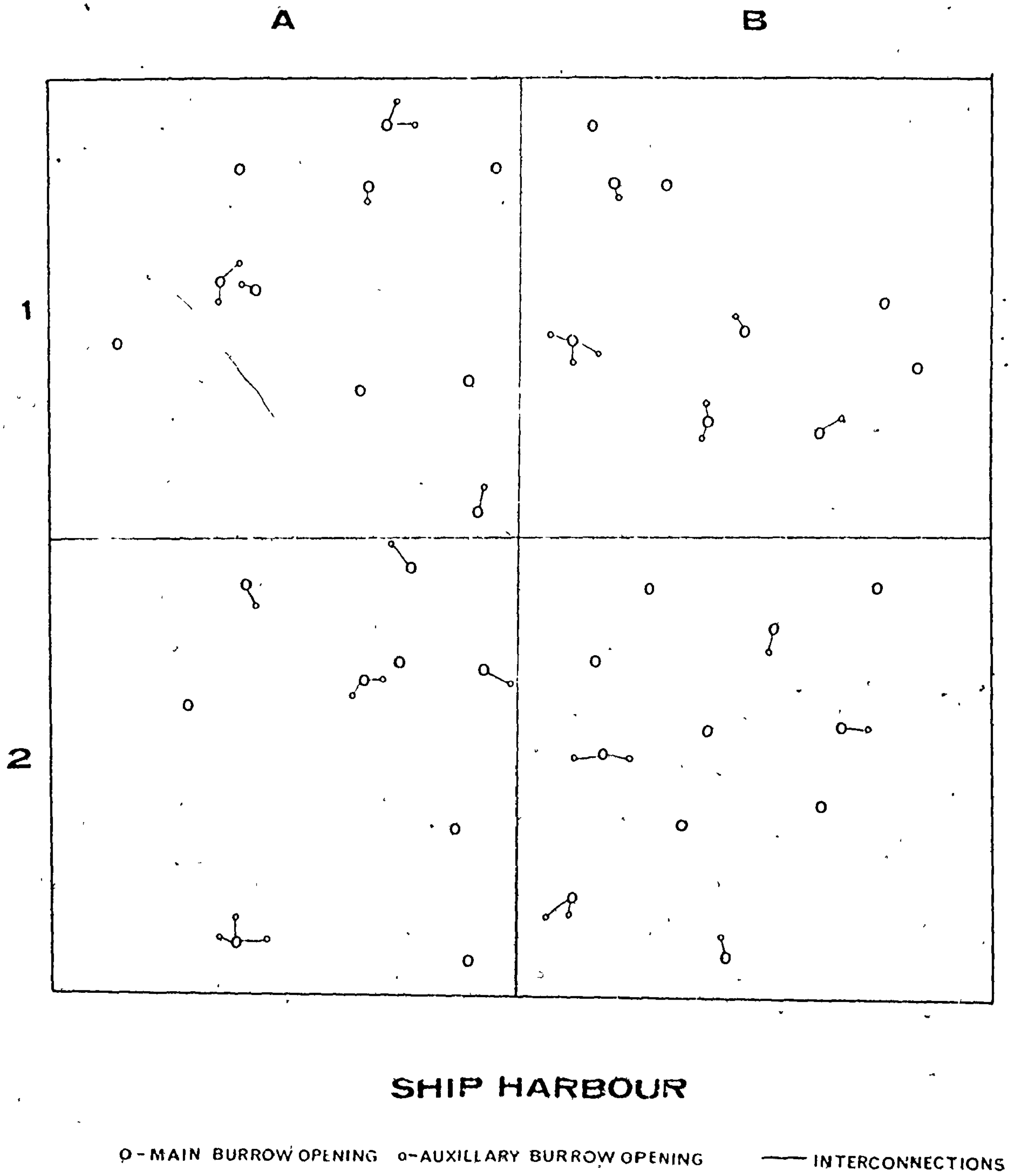


Fig. 3-5: Distribution of *Axius serratus* burrows in Ship Harbour (area size 2m. X 2m.).

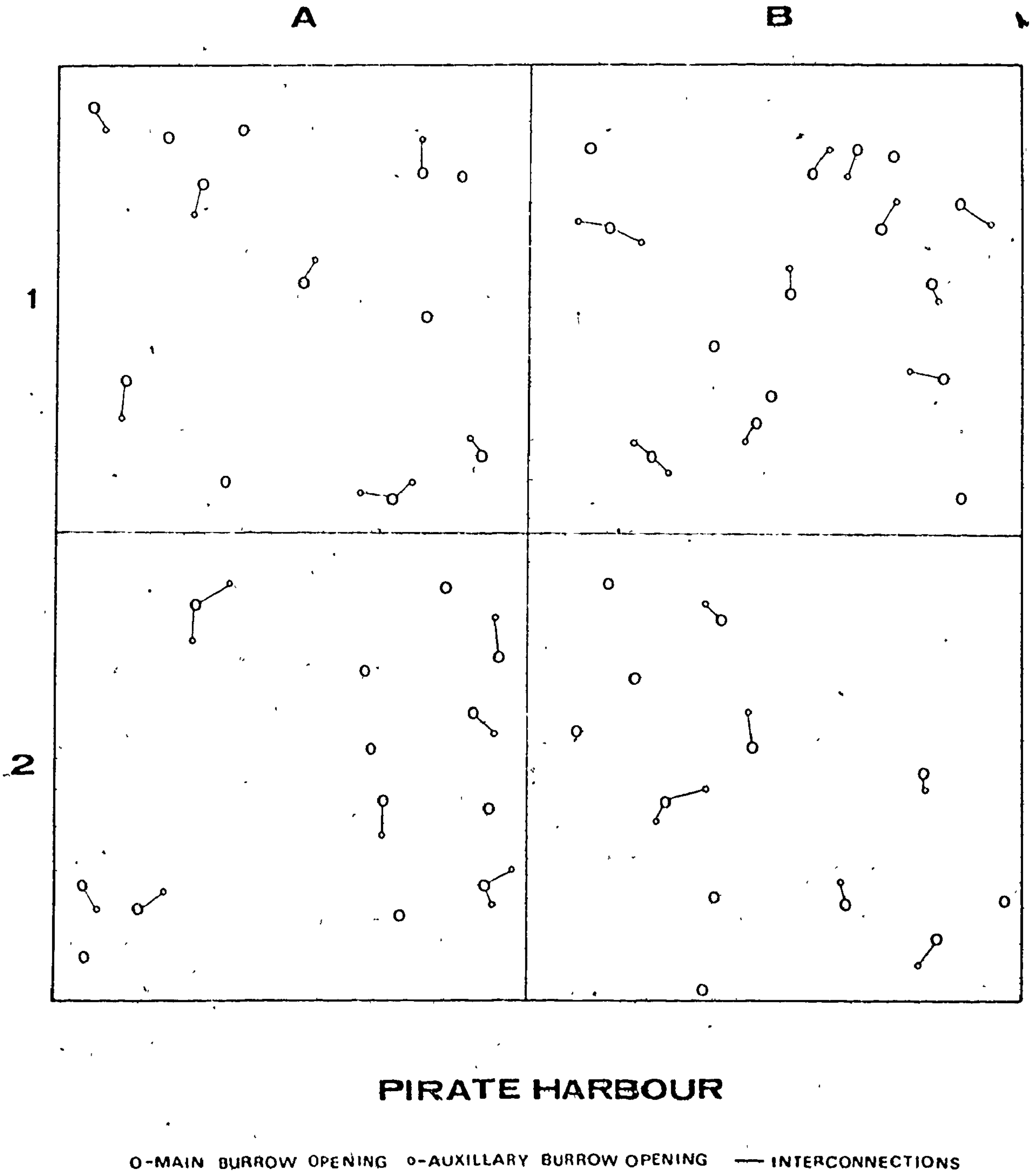


Fig. 3-6: Distribution of *Axius serratus* burrows in Pirate Harbour (area size 2m. X 2m.).

Table 3-4: Results of the Distance to nearest neighbour.

A. SHIP HARBOUR

Location	N	P	Σr	Σr^2	$\bar{r}_A$	$\bar{r}_B$	R	C	σ_{r_E}	Size
S.H.-20	10	.001	194	4342	19.4	15.8128	1.227	1.373*	2.614	1m x 1m
S.H.-21	9	.0009	223	6895	24.78	16.67	1.457	2.793**	2.904	✓
S.H.-22	✓	✓	151	3241	16.78	16.67	1.007	.038	2.904	✓
S.H.-23	11	.001	259	6295	23.55	15.08	1.562	3.562**	2.376	✓
Ship Harbour Total	39	.000975	858	21596	22	16	1.375	4.478**	1.34	2m x 2m

B. PIRATE HARBOUR

Location	N	P	Σr	Σr^2	$\bar{r}_A$	$\bar{r}_B$	R	C	σ_{r_E}	Size
P.H.-50	12	.0012	226	4988	18.83	14.43	1.305	2.02*	2.178	1m x 1m
P.H.-51	13	.0013	218	4256	16.77	13.87	1.21	1.44	2.011	✓
P.H.-52	12	.0012	447	4144	20.58	14.43	1.43	2.82**	2.178	✓
P.H.-53	15	.0015	232	5303	15.47	12.91	1.20	1.47	1.742	✓
Pirate Harbour Total	52	.0013	923	1861	17.75	13.88	1.28	3.86**	1.005	2m x 2

* C = 1.96, P = .05: significant

** C = 2.58, P = .01: highly significant

Table 3-5: Random burrow densities taken from Ship Harbour, each quadrat is one square meter.

Quadrat No.	Total No. of burrows	No. of main burrow openings	No. of auxiliary burrow openings	Total No. of burrow complexe
S.H. - 200	16	10	6	10
S.H. - 201	17	9	8	9
S.H. - 202	17	9	8	9
S.H. - 203	18	11	7	11
S.H. - 204	12	7	5	7
S.H. - 205	12	9	3	9
S.H. - 206	18	10	8	10
S.H. - 207	12	8	4	12
S.H. - 208	10	7	3	7
S.H. - 209	14	10	4	10
S.H. - 210	18	11	7	11
S.H. - 211	14	9	5	9
S.H. - 212	15	9	6	9
S.H. - 213	14	8	6	8
S.H. - 214	12	7	5	7
S.H. - 215	14	8	6	8
S.H. - 216	10	7	3	7
S.H. - 217	12	9	3	9
S.H. - 218	13	9	4	9
S.H. - 219	14	8	6	8

Table 3-6: Random burrow densities taken from Pirate Harbour, each quadrat is one square meter.

Quadrat No.	Total No. of burrows	No. of Main burrow openings	No. of auxiliary burrow openings	Total No. of burrow complexes
P.H.-100	19	12	7	12
P.H.-101	27	15	12	15
P.H.-102	22	13	15	13
P.H.-103	18	10	8	10
P.H.-104	26	15	11	15
P.H.-105	20	12	8	12
P.H.-106	21	13	8	13
P.H.-107	21	14	7	14
P.H.-108	16	10	6	10
P.H.-109	15	11	4	11
P.H.-110	19	12	7	12
P.H.-111	14	9	5	9
P.H.-112	17	10	7	10
P.H.-113	18	12	6	12
P.H.-114	23	14	9	14
P.H.-115	19	13	6	13
P.H.-116	24	15	9	15
P.H.-117	14	10	4	10
P.H.-118	15	9	6	9
P.H.-119	17	11	6	11

Table 3-7: Coefficient of dispersion for *Axius serratus*, in Strait of Canso.

	Number of Quadrats	Total number of burrows	Ave. Mean density (no. /sq.m)	Coefficient of dispersion
I Pirate Harbour				
A. Total number of burrows (main openings plus auxiliary openings)	20	385	19.25	.7429
B. Burrow complexes	20	240	12	.3246
II Ship Harbour				
A. Total number of burrows (main openings plus auxiliary openings)	20	282	14.1	.4621
B. Burrow complexes	20	175	8.75	.1789

Limits of the coefficient of dispersion for random distribution at n = 20;

0.3342 - 1.6658

The Ship Harbour sample population was significantly uniformly spaced, or over-dispersed ($R = 1.375$, $c = 4.478$; $p < 0.01\%$). The Pirate Harbour population showed a similar pattern ($R = 1.28$, $c = 3.86$; $P < 0.01\%$).

b. Coefficient of dispersion

In the determination of the coefficient of dispersion, twenty quadrat counts were made in each area. Within each square meter quadrat counts were made to determine the total number of burrows, the number of main burrow openings, the number of auxiliary burrow openings, and the total number of burrow complexes (Tables 3-5 and 3-6). In each area a coefficient of dispersion was obtained for the total number of burrow complexes (Table 3-7).

In Pirate Harbour the mean density (number per square meter) of the total number of burrow openings is 19.25, with a corresponding coefficient of dispersion of 0.7429; the number of burrow complexes shows a mean density of 12, with a corresponding coefficient of dispersion of 0.3246. Similarly, the mean density of burrow openings in Ship Harbour is 14.1, with a corresponding coefficient of dispersion of 0.4621, and a mean density of burrow complexes of 8.75, corresponding to a coefficient of dispersion of 0.1789.

The limits of the coefficient of dispersion for random distribution at $n = 20$ are 0.3342 - 1.6658. Analysis of of this data reveals that in both Ship Harbour and Pirate Harbour extreme care must be taken in the determination of the number of burrows present. When all burrow openings (main openings plus auxiliary openings) are counted, the coefficient of dispersion falls within the limits of a random distribution. When only the number of burrow complexes is used, the coefficient of dispersion indicates a uniform distribution.

4. Discussion

Both techniques used illustrate that the burrows of Axius serratus have a uniform spatial distribution. Reasons for a uniform distribution may include either competition for food, living space, and reproduction, or the nature of the environment.

It has been suggested by Connell (1956) among others, that social pressures may cause organisms to space themselves out so that each animal has an adequate living space and food supply. Holme (1950) has shown that the deposit feeding bivalve Tellina displays a uniform distribution pattern which is correlated with the foraging activities of the inhalent siphon on the mud surface. The scavenging decapod crustacean Uca also exhibits a uniform distribution; of two species studied U. pugilator (Crame, 1941; Teal, 1958; Weis, 1976) and U. pugnax (Pearse, 1914; Weiss, 1976) both were found to be extremely territorial. Connell (1963) studied the grazing behaviour of <u>Erichthonius braziliensis</u>, an amphipod which builds tubes on solid surfaces, and suggested that the uniform distribution observed was related to food gathering. Johnson (1959) studying the spatial distribution of <u>Phoronopsis viridis</u>, a tube building worm-like organism, attributed uniform spacing to the competition for space necessary for the expansion of the lophophore during feeding.

The need for living space may also influence the spatial distribution of organisms. Studies conducted on barnacles by Connell (1961) and Crisp (1961) indicate that newly-settled larvae exhibited a uniform spacing pattern. The tube-building, sabelled polychaete <u>Spirorbis boreali</u> also exhibits a uniform distribution, due to the need for living space (Wisely, 1960). Recently, many studies have been conducted on the spatial pattern displayed by the Norway lobster, <u>Nephrops norvegicus</u> (Dybern and Hoiseter, 1965; Chapman and Rice, 1971; Atkinson, 1974; Farmer, 1974). Considerable variation has been found to exist in the spatial pattern of the burrows from aggregations (Dybern and Hoiseter, 1965; Chapman and Rice, 1971) to random (Atkinson, 1974) to uniform (Farmer, 1974). All studies agree, however, that in the presence of high densities, territorial behaviour is strong and a degree of spacing will result.

Considerable importance has also been placed on the nature of the substrate in regulating the distribution of benthic organisms. Gage and Geekie (1973) have shown that in Scottish sea-lochs the fauna of current-swept muddy sand bottoms are more aggregated than the fauna of usually deeper, soft mud areas. Variation in the substrate has been cited as the main cause in the aggregational distribution of the filter feeding bivalves Mya and Petricola (Connell, 1956) and Modiolus demissus (Connell, 1963).

Table 3-8 summarizes results that indicate a differentiation between certain trophic types and their spatial distribution. Deposit feeders and grazers seem to be distributed uniformly, except where population densities are low and the competition for space is slight. Filter feeders commonly exhibit aggregated distributions, probably as a result of their relative immobility and the disperse nature of their food source.

Ship Harbour and Pirate Harbour exhibit large local variations in the physical properties of the sediment (see Chapter 6 for discussions). Since no difference was found in the spatial arrangements of the burrows in the two areas, apart from the mean density, local variations in the substrate seem to exert little influence on the spatial distribution of Axius serratus. It is concluded that the distribution found in the Axius serratus population is a result of exploitation of the sediment in the search for food.

Table 3-8: A comparison of the population dispersion of various sedentary marine organisms.

Type of feeding	Species	Dispersion pattern	Authority
Deposit feeder	*Nucula proxima*	clumped	Levinton (1972)
	Spirorbis boreali	uniform	Wisely (1960)
	Tellina tenuis	uniform	Holme (1950)
	Uca pugilator	uniform	Teal (1958)
	Uca pugnax	uniform	Connell (1963)
Grazer	*Erichthonius braziliensis*	uniform	Connell (1963)
Suspension feeder	*Mya arenaria*	clumped	Connell (1956)
	Petricola pholadiformis	clumped	Connell (1956)
	Modiolus demissus	clumped	Connell (1963)
	Barnacles	uniform	Crisp (1961)
	Phoronopsis viridis	uniform	Johnson (1959)

As stated earlier, extreme care must be taken to ensure that only burrow complexes are used in the analysis of spatial relationships. The intermixing of auxiliary openings connected to main burrow openings or burrows of other organisms may result in erroneous results. In the analysis of the spatial distribution of Nephrops norvegicus, Chapman and Rice (1971) may have used all burrow openings in the area sampled, which not only consisted of main openings, but also auxiliary openings and burrows of the crab Goneplax rhomboides. This may have affected the results obtained as outlined in Atkinson (1974).

D. Field Observations

1. Burrow Openings

Burrow openings were observed in water depths ranging from 7.5 m. to 11.4 m. in both Ship Harbour and Pirate Harbour. The presence of occupied burrows, along with their linkages, was determined by forcing potassium permanganate solution, from plastic wash bottles, into them and recording from which openings the pink dye was expelled.

It was observed that large burrow openings (2.5 to 3 cm.) are associated with either 0, 1, 2 or 3 smaller openings (0.5 to 1.5 cm.). In Ship Harbour, most burrow complexes consisted of either one main opening (49%) or one main opening and one auxiliary opening (31%); other complexes consisted of two auxiliary openings (15%) and three auxiliary openings (5%) (Table 3-9). Pirate Harbour, on the other hand, was dominated by a single main opening (42%) and one main opening and one auxiliary opening (46%); the remaining 12% consisted of one main opening and two auxiliary openings (Table 3-10). This variation in the configuration of burrow complexes has been observed in other burrowing shrimps and lobsters. Rice and Chapman (1971) noted that burrow complexes of the lobsters <u>Nephrops norvegicus</u> had the following frequencies: one opening (31%); two openings (26%); three openings (28%); more than three openings (15%). Karplus <u>et al</u>. (1974) also observed a variation of burrow complex configuration in the shrimp <u>Alpheus</u>: one opening (17%); two openings (47%); three openings (22%); more than three openings (14%).

The openings of <u>Axius serratus</u> (Plate 3-1) lacked the "volcano-like" mound that has been reported in association with other burrowing thalassinids (Stevens, 1929; MacGintie, 1930, 1934; Pearse, 1945). Openings similar to <u>Axius</u> have been observed by Braithwaite and Talbot (1972) on <u>Alpheus</u> burrows, and by Farrow (1971) for <u>Neaxius</u> burrows.

2. <u>Burrow Morphology</u>

Burrow morphologies were determined from polyester resin casts. The extracted casts were analyzed for size, shape, surface features and any other properties deemed important. Due to the nature of the substrate, it was

Table 3-9: <u>Axius serratus</u>. Relative proportions of different burrow types found occupied in the Ship Harbour study area

Quadrat	Single Opening		One Main Opening one auxiliary hole		One Main Opening two auxiliary holes		One Main Opening three auxiliary holes	
	No.	%	No.	%	No.	%	No.	%
S. H. - 20	5	50	3	30	2	20	-	-
S. H. - 21	4	45	3	33	1	11	1	11
S. H. - 22	4	45	3	33	1	11	1	11
S. H. - 23	6	55	3	27	2	18	-	-
Ship Harbour Total	19	49	12	31	6	15	2	5

Table 3-10 Axius serratus. Relative proportions of different burrow types found occupied in the Pirate Harbour study area.

Quadrat	Single Opening		One Main Opening one auxiliary hole		One Main Opening two auxiliary holes	
	No.	%	No.	%	No.	%
P. H. -50	5	42	6	50	1	8
P. H. -51	6	47	5	38	2	15
P. H. -52	5	33	8	54	2	13
P. H. -53	6	50	5	42	1	8
Pirate Harbour Total	22	42	24	46	6	12

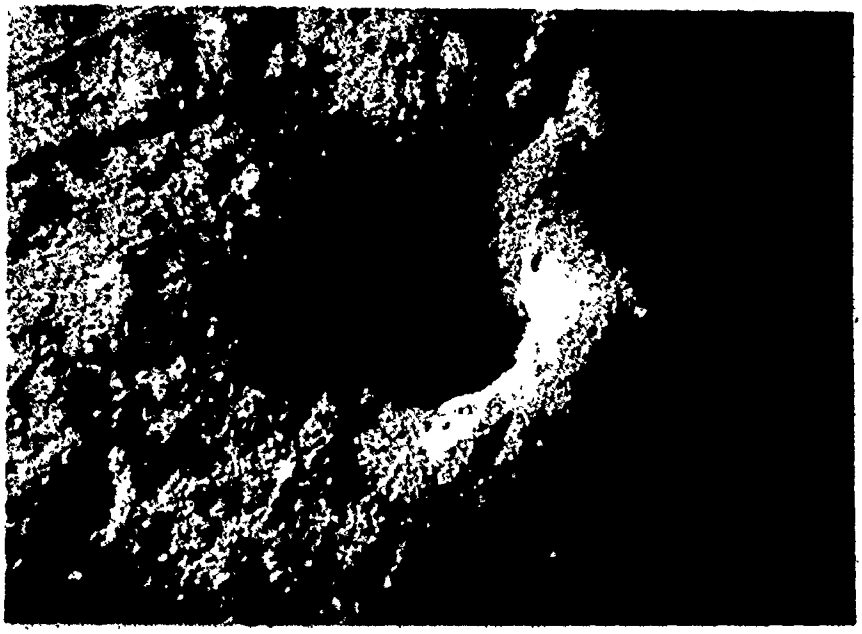


Plate 3.1: External morphology of *Axius* burrow, in Ship Harbour.

impossible to recover casts in Pirate Harbour, thus the discussion will be limited to Ship Harbour and the geologic and biologic implications suggested by these casts.

Several casts were made of *Axius* burrows in Ship Harbour (Plates 3-2, 3-3, 3-4). Since the three main casts display similar properties, detailed analysis will be limited to cast C-3 (Plate 3-2). The polyester resin cast is 2.9 m. long with an average diameter of 3.5 cm. Due to the settling effect of the resin, the top 20 cm. of the burrow is not represented. It is believed from the burrow configuration at the base that the cast represents the total length of the burrow (see also cast C-5, Plate 3-3). Obvious horizontal branches are not reproduced (due possibly to a lack of resin when pouring).

The burrow is a simple, branching structure that possesses three central chambers and possibly three horizontal components. The chambers are thought to serve as somersaulting areas, as in the burrows of *Callianassa* and *Upogebia* (MacGinitie, 1934; Farrow, 1971), thus allowing the shrimp free movement up and down its burrow length. The bottom of the burrow branches horizontally for 39 cm. and then terminates abruptly in a swollen chamber.

In cross-section, *Axius* burrows display half-moon configurations, which have been attributed to movements of the animal in its burrow (Shinn, 1968). Shinn's hypothesis

Plate 3-2: Polyester resin cast (C-3) of Axius burrow from Ship Harbour.

Plate 3-3: Polyester resin cast (C-5) of Axius burrow from Ship Harbour.

Plate 3-4: Polyester resin cast (C-1) of Axius burrow from Ship Harbour.

is that when the animal moves about it bumps the roof of the tunnel with its back, loosening sediment which falls to the floor, which in turn is flattened out by the legs and tail of the animal. The result would be a cross-section displaying a smooth floor and a bumpy irregular roof (Figure 3-7). This type of cross-section has been reported for the shrimp genera Alpheus (Shinn, 1968; Farrow, 1972; Karplus et al., 1974), the stomatopod Squilla (Shinn, 1968), and the lobster Nephrops norvegicus (Rice and Chapman, 1971). Burrows found in cores obtained from the Atlantic Geoscience Center also display this half-moon cross-section (Plate 3-5). Unlike Shinn's horizontal orientation, however, Axius burrows also exhibit a vertical half-moon configuration (Figure 3-8), and Shinn's movement hypothesis therefore does not apply.

The increase in water content of fine-grained muds by biogenic activity may result in the creation of muds that display a pseudo-thixotropic nature (Rhoads, 1970). These muds become more fluid with increasing magnitude, duration, or rate of the stresses applied to them. Because of the thixotropic effect, extensive water movement may regularly lower the stability of a sediment. To overcome this instability, it has been noted that many thalassinid crustaceans line their burrows (Weimer and Hoyt, 1964; Shinn, 1968; Farrow, 1971). This lining may be of a chemical nature, such as the secretion of collophanite by Callianassa (Weimer and Hoyt, 1964); or of an organic nature, such as

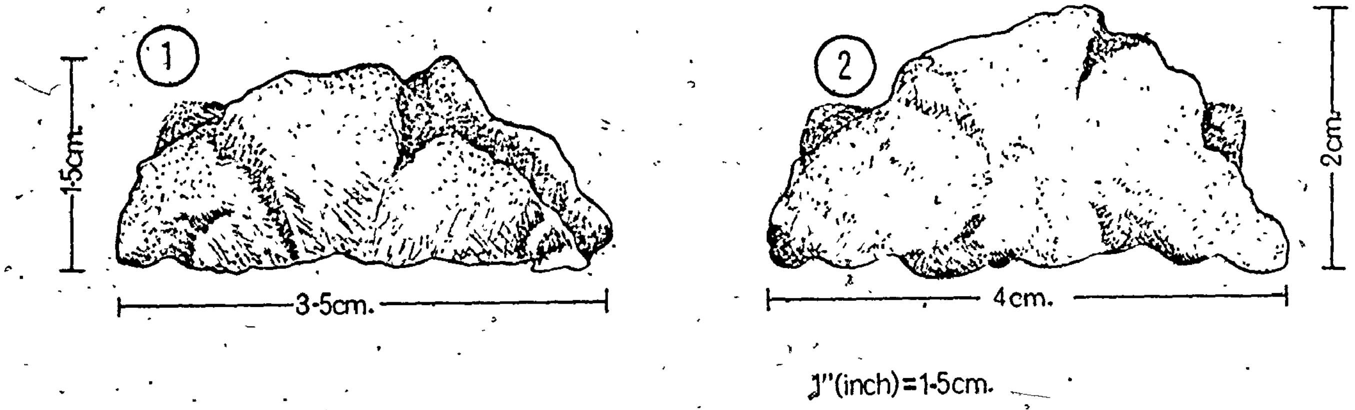


Fig. 3-7: Cross-section of Cast C-1 (1)
Cross-section of Case C-2 - (2)

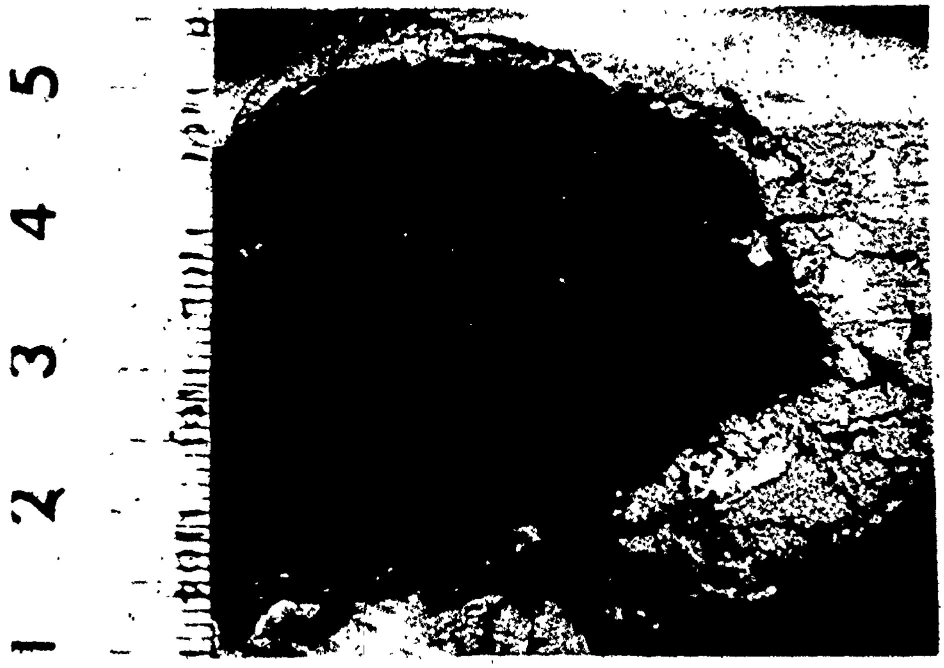


Plate 3-5: Cross-section of *Axius* burrow in core from Pirate Harbour. Note the oxidized halo surrounding the burrow.

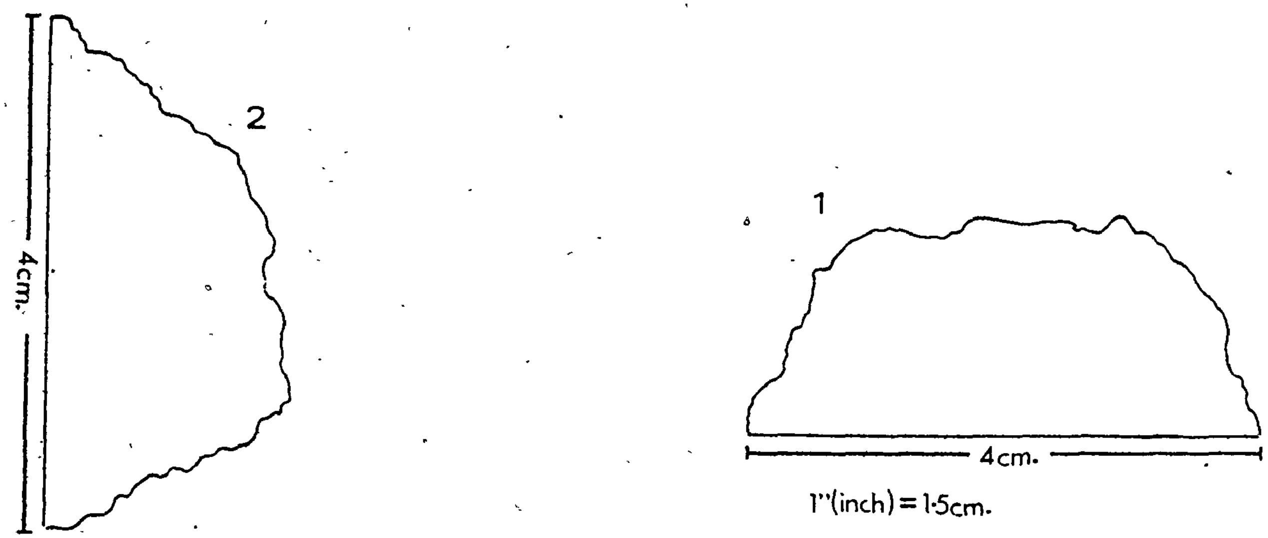


Fig. 3-8: 1. Cross-section showing horizontal orientation of Shinn's burrow (Shinn, 1968)

2. Cross-section showing vertical orientation of Canso burrow (Cast, C-3)

the linings of burrows with eel grass by Alpheus (Farrow, 1971) and Nephrops (Rice and Chapman, 1971). Axius burrows in the Canso area were lined with eel grass and other organic substances, thought to be of fecal origin. Since few distinct crustacean pelletoidal grains were found at the sediment-water interface, it is believed that Axius lines its burrow with fecal remains. This may also explain the nodose surface texture displayed by the casts.

3. Implications of Burrow Morphology

Perhaps the most striking feature of Axius burrows, as typified by cast C-3, are their great vertical extent. Depth of the burrowing activity of thalassinid decapod crustaceans seems to be extremely variable. Frey and Mayou (1971) have traced Callianassa burrows 2 m. into the substrate, while Pryor (1973) has recovered live shrimp (Callianassa atlantica) from as deep as 4 m. within the substrate. Karplus et al. (1974) have traced Alpheus burrow complexes 55 cm. deep. Details of other occurrences of shrimp burrows of Callianassa, Upogebia, Alpheus and Neaxius seems to conform with an average burrow length of about 1 m. (Shinn, 1968; Farrow, 1971; Braithwaite and Talbot, 1972). Axius serratus burrows thus represent the deepest (2.3 m.) verified occurrence of thalassinid burrowing.

Early investigators (Seilacher, 1967; Rhoads, 1967;

Frey, 1970) believed that burrowing depth was a function of the physical parameters of the environment. Relatively deep burrows (greater than 50 cm.) were thought to be restricted to intertidal zones where they provided protection against a fluctuating environment (Frey, 1970). While in subtidal areas, where environmental conditions are more stable, shallow horizontal burrows dominated. More recent studies (Farrow, 1971; Braithwaite and Talbot, 1972; Pryor, 1973) have expanded this theory to include substrate variability and food partitioning. Farrow (1971) states that the burrowing depth of crustaceans in Aldabra Atoll is a function of the ability of the organism to utilize the maximum amount of sediment for food. Thus, burrow depth may be limited only by the characteristics of the substrate, and the burrow terminates when the organism can no longer dig through the sediment.

Feeding may be the factor controlling burrow depth in Axius serratus. Previously, it was shown that the burrows of Axius display a high degree of spacing, which suggests a negative interaction between individuals. In the relatively quiet water harbours of the Strait of Canso, which possess thick expanses of fine-grained sediment, the development of vertically orientated burrow systems would be the most efficient mechanism for food partitioning.

The general geometry of the burrow of Axius serratus suggests that it served both as a secure dwelling and as a means of sediment exploitation. Although not enough specimens were captured for gut analysis, certain inferences can be made from studies on related thalassinid genera. Perhaps the closest relative to <u>Axius</u> is the deep-water genera <u>Calocaris</u>. Stomach analysis conducted by Buchanan (1963) on <u>Calocaris</u> revealed large quantities of unsorted bottom mud and forams (no macro-faunal remains were found). From this, Buchanan (1963) suggested that <u>Calocaris</u> obtained its food through the non-selective swallowing of sediment. MacGinitie (1934) and Pohl (1946) likewise demonstrated that the food of most North American callianassids consisted of macro-organisms and organic debris obtained by actively sifting sediment. The half-moon cross-section displayed in <u>Axius</u> burrows and interpreted by Shinn (1968) as the result of shrimp movement (in the genus <u>Alpheus</u>) may well be the result of sediment mining. The tunnels and chambers are oversized and stabilized by some means. Occasionally concentric banding was observed on the flat side of the burrow. Two plausible explanations for this exist:

(i) it is the result of simply redistributing loose sediment that has fallen into the burrow from the surface (Shinn, 1968);

or (ii) it may be a result of burrow accretion (Braithwaite and Talbot, 1972).

The latter explanation may involve a number of interactions.

MacGinitie (1934) has suggested that the burrow systems of deposit feeding thalassinids must be extended as particular areas are exhausted of their food supply. _Axius_ burrows vertically through the maximum depth of sediment available for exploitation and each burrow system is separate from that of its neighbour and are of only limited lateral extent. Such a geometric form reflects maximum utilization of a unit volume of sediment, and is clearly of benefit to a deposit feeding organism. In order to extend the burrow it is thought that the shrimp may seize sediment from the bumpy irregular wall, pass it through its body, and incorporate it onto the flat side with the aid of its telson. Thus, the burrow undergoes a slow lateral accretion. The lateral migration of _Alpheus_ burrows has been noted earlier by Braithwaite and Talbot (1972) and Karplus _et al_. (1974), yet no mechanism was postulated.

In the excavation of _Axius_ burrows, it was noted that large amounts of marine grass were incorporated in the burrow walls and in certain chambers within the burrow. Comparable detritus has been observed in the walls and chambers of the shrimp _Neaxius_ (Farrow, 1971), _Callianassa_ (Shinn, 1968; Farrow, 1971; Braithwaite and Talbot, 1972), _Alpheus_ (Frey and Howard, 1975), and the stomatopod _Pseudosquillia ciliata_ (Braithwaite and Talbot, 1972). These pockets of grass have been interpreted as:

(i) caches of materials too bulky to be removed easily from the burrow, and thus a normal aspect of burrow construction (Farrow, 1971);

and (ii) media for the culture of edible bacteria (Braithwaite and Talbot, 1972).

It is known that various organisms, such as the polychaete Nereis diversicolour and the crab Cardiosoma quanhumi, store plant matter for later feeding (Pettibone, 1963; Herreid, 1963).

In a recent review on this subject, Frey and Howard (1975) agree with the postulate that the grass is utilized to culture edible bacteria, and question whether this is an active or passive mechanism. During reconnaissance diving while investigating Axius burrows, it was observed that numerous burrow openings had eel grass surrounding them (Plate 3-6), and on several occasions these grasses were actively seized by the shrimp and taken into the burrow. The distribution of the grasses in Axius burrows suggest that they could be used not only as a lining material (on the walls), but also as a media for the culturing of bacteria (in chambers).

Many investigators have recently shown that in fine muds, deposit feeding organisms are responsible for the aeration of the sediment in which they live (Frey, 1970; Rhoads and Young, 1971; Howard and Frey, 1973). The reworking of fine-grained muds leads to the maintenance of oxygen

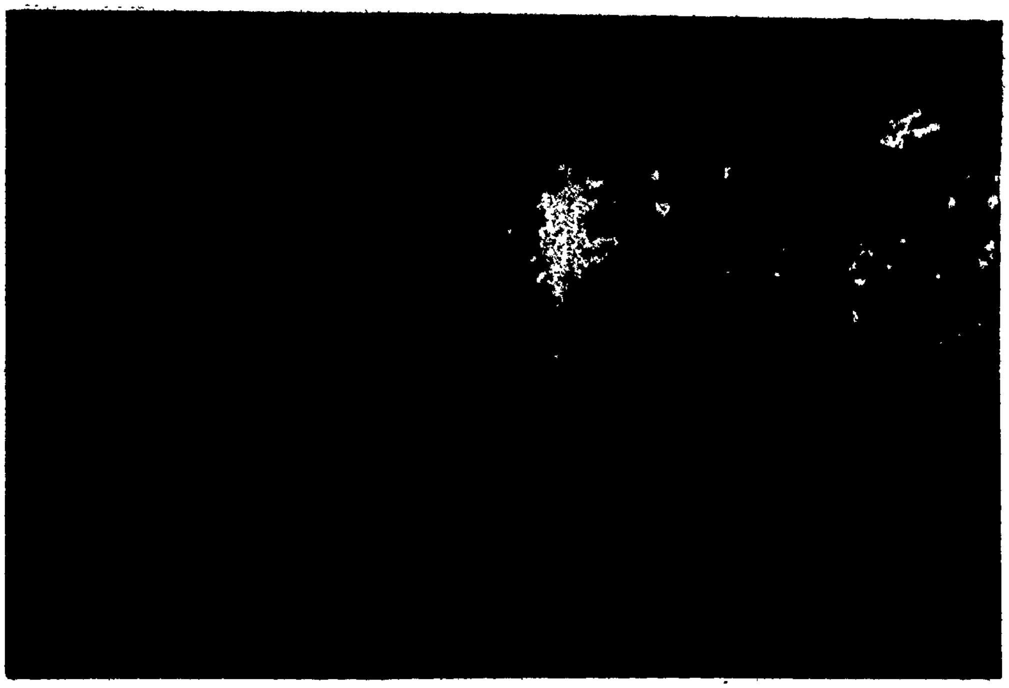


Plate 3.6. *Axius* burrow displaying eel grass incorporated in burrow wall and near burrow opening.

levels in the host sediment. It has been shown that deposit feeding organisms, other than anaerobic forms, must communicate with the surface and derive oxygen from the overlying water column (Frey, 1970). Oxygen is thus brought into the sediment as the organism pumps water through its burrow or while respirating while in contact with the sediment (Howard and Frey, 1973).

In general this aeration of the sediment is conspicuous in fresh cores as a light-coloured halo surrounding the burrow, which contrasts with the black oxygen-deficient matrix. These halos may remain as zones of increasing permeability in the sediment. A variety of deposit feeding organisms have been shown to significantly increase the oxygen levels of sediments. Rhoads and Young (1971), state that the holothurian Molpadia oolotica is responsible for oxidizing the sediment to a depth of 9 cm. in Cape Cod Bay. The capitellid polychaete Heteromastus maintains a connection with the sediment-water interface, while feeding at depth (25 cm. below the surface) (Schafer, 1972). Howard and Frey (1973) have shown that an oxidized halo surrounds the burrow of Heteromastus. This halo ranges in thickness from 2 to 4 mm., and can be traced along the entire extent of the burrow.

Cores taken in the Strait of Canso contain numerous burrows attributed to Axius serratus (similar depth of core). The introduction of oxygenated water to such depths in the sediment may exert strong influences on the trace metal distribution (see Chapter 6 for discussion).

Perhaps the most important feature of Axius serratus burrows, in connection with the sediment, involves the increase in area of the sediment-water interface. Burrows may be thought of as extensions of this interface and are thus zones of increased microbial activity, increased geochemical reaction sites, and potential sites for subsequent migration of metal chelates. Analysis of burrow geometry and density indicates that in the study area, Axius serratus burrows increase the area of the sediment-water interface by a factor of at least five. The consequences of this increase will be discussed in Chapter 6.

4. Burrow Regeneration

During the course of the study, several quadrats, one meter square, were disturbed using the suction dredge. All existing burrow openings were destroyed to a depth of approximately 50 cm. After twenty-four hours, the area was re-examined and all burrow openings were noted. In most instances, it was observed that every burrow was re-opened and occupied. Spatial relationships were not altered, and density counts remained the same. This indicates that the shrimp, Axius serratus, is capable of moving large amounts of sediment in a short time span.

5. Juvenile Burrows

During the study of Axius burrows in Ship Harbour, an unusual polyester resin cast was recovered. Unlike the other systems, this cast possessed a chamber with smaller burrows radiating from it (Plate 3-7). The complex exhibited similar properties to a cast of an Upogebia affinis burrow described recently by Frey and Howard (1975). They postulated that these smaller burrows may be:

(i) the burrows of juvenile shrimp;

(ii) independent burrows by a commensal;

or (iii) a subsequent inhabitant of the adult burrow.

Subsequent analysis lead the authors to believe that the burrows were in fact produced by juveniles, which after the initial planktonic stage, re-entered the burrows of the adult to establish their initial burrows.

Studies of the life history of thalassinid crustaceans are rare. Gurney (1942), in a classic work on decapod larvae, concludes that most species exhibit a free-swimming pelagic, larval stage. On the other hand, Forbes (1973) has illustrated that larvae of Callianassa kruassi never leave the parent burrow, and he reported juvenile shrimp burrows radiating off the parent burrows. Likewise, the free-swimming larval stage has been suppressed in Upogebia savignyi (from the Red Sea); the young have an almost adult form when they are hatched and remain with the adults in the chambers of

Plate 3.7: Polyester resin cast of Axius burrow from Ship Harbour: Note central chamber with smaller burrows (juvenile?) radiating from it.

sponges (Gurney, 1937). A close relative of Axius, Calocaris, has received detailed study by Buchanan (1963). He states that the larvae, reared in the laboratory, showed a marked reluctance to swimming and concluded that a pelagic phase in larval development was very remote. Thalassinids thus are very plastic genetically, and distinctive adaptations of one kind or another are widespread among the different species (Frey and Howard, 1975).

The possibility that the structures illustrated (Plate 3-7) are commensals cannot be ruled out completely. Thalassinid burrows offer numerous examples of commensalism (see MacGinitie and MacGinitie, 1968, for review). Numerous dredgings of Axius burrows yielded no associated organism that could be repsonsible for the creation of the secondary burrows.

The structure illustrated can be defined in ichnofossil terminology as an association of Ophiomorpha (adult burrow) and Thalassinoides (juvenile burrows). A similar fossil analog was recently described from Pleistocene deposits in North Carolina (Curran, 1976). It is speculated that the secondary burrows in cast C-6 were created by juvenile Axius shrimps in the adult burrow. Dredging in Ship Harbour resulted in the capture of a juvenile (Figure 3-1) from a burrow which was obviously oversized. Further work on the life history of Axius serratus is necessary in order to yield better criteria for resolving this matter.

CHAPTER FOUR

BIOTIC ASSOCIATES

A. Introduction

In addition to Axius, several other organisms in the study area are capable of modifying the sediment. Earlier reports on the distribution of specific taxa in the Strait of Canso area include: Mollusca (Wagner, 1975), Ostracoda (Cole and Ferguson, 1975), and Foraminifera (Cole and Ferguson, 1975; Vilks et al., 1975).

A faunal sampling regime was conducted in both subareas, including surface sampling by divers, and subsurface sampling by means of the portable suction dredge. Due to the low number of species present, quantitative samples were not taken; except for the subsurface work, where densities could be estimated from the size of the area being dredged. Live organisms were captured and placed in portable aquaria for observations.

B. Distribution of Common Trace-Making Organisms

A number of marine invertebrates and several kinds of dimersal fish are capable of leaving traces in the sediments of the Strait of Canso area. The distribution of the most common forms in Ship Harbour and Pirate Harbour is given in Table 4-1. A detailed community analysis was not attempted and thus Table 4-1 is only a partial representation of the total community. The relative densities of the more important forms were estimated.

1: Ship Harbour

Most of the discharge from the major industries in the area is into Ship Harbour. The fine-grained sediments of this sheltered harbour are inhabited by a few macro-organisms. As determined from the suction dredge samples, the community is dominated by the polychaetes Nereis virens, Scoloplos armiger, Ninoe nigripes, the nemertean Cerebratulus marginatus, and the crustaceans Crangon septemspinosa, Pagurus acadianus and Axius serratus. In addition, numerous dimersal fish were also observed: Pseudopleuronectes americanus (common flounder), Myoxcephalus scorpius (short-horn sculpin), Myoxcephalus octodemspinsus (long-horn sculpin), and Raja (various species of the common skate).

2. Pirate Harbour

Pirate Harbour supports a more diverse community. The industrial outfalls, across the Strait, exert little influence on Pirate Harbour due to the nature of the currents in the middle of the Strait. The bottom sediments are

Table 4-1: Distribution of major trace-making organisms in Pirate Harbour and Ship Harbour

A. PIRATE HARBOUR

Polychaetes:	*Nereis virens* *Ninoe nigropes* *Scoloplos armiger*
Nemertean:	*Cerebratulus marginatus*
Crustaceans:	*Axius serratus* *Homarus americanus* *Cancer irroratus* *Pagurus acadianus* *Crangon septemspinosa*
Gastropod:	*Lunatia heros*
Bivalves:	*Astarte undata* *Mercenaria mercenaria* *Modiolus modiolus*
Dimersal fish:	*Pseudopleuronectes americanus* *Myoxcephalus scorpius* *Myoxcephalus octodemsponsus* *Raja* sp.

B. SHIP HARBOUR

Polychaetes:	*Nereis virens* *Scoloplos armiger* *Ninoe nigropes*
Nemertean:	*Cerebratulus marginatus*
Crustaceans:	*Axius serratus* *Crangon septemspinosa* *Pagurus acadianus*
Dimersal fish:	*Pseudopleuronectes americanus* *Myoxcephalus scorpius* *Myoxcephalus octodemsponsus* *Raja* sp.

composed of mixtures of sand, silt and clay and are physically more stable than the finer-grained sediments of Ship Harbour (see Chapter 6 for discussion). The Pirate Harbour community includes: the bivalves, Astarte undata, Mercenaria mercenaria, and Modiolus modiolus; the polychaetes, Nereis virens, Ninoe nigripes, and Scoloplos armiger: the nemertean, Cerebratulus marginatus; the crustaceans, Homarus americanus, Axius serratus, Cancer irroratus, Pagurus acadianus and Crangon septemspinosa; the gastropod, Lunatia heros; as well as unidentified urchins and sea stars. In addition, the same dimersal fish found in Ship Harhour are also found here.

C. Notes on the Natural History of the Major Trace-Making Organisms

1. Nereis virens

The polychaete Nereis virens (Plate 4-1) belongs to the family Nerediidae, and is a common element of the biota in both Ship Harbour and Pirate Harbour. Nereis has been shown to be an extremely important agent in the bioturbation of marine muds. In the Great Bay estuarine system in New Hampshire, Winston and Anderson (1970) conclude that the greatest amount of bioturbation was observed where polychaetes of the genus Nereis occurred.

Nereis virens creates semi-permanent mucous-lined burrows that reach a maximum depth of 40 cm. and are 4 to 6 mm. in diameter. Schafer (1972) describes the movement of

Plate 4-1: Nereis virens from Ship Harbour (scale bar in cm.).

Nereis through the sediment as a bolting action. The proboscis opens a cavity in the sediment in front of the animal and the worm crawls into the newly created cavity by pushing with the parapods and by peristaltic movements of the body. The bolting and peristaltic movements enable Nereis to pass through almost any kind of sediment; coarse sand, fine sand, mixtures of sand and mud, pure mud, and even consolidated clay (Schafer, 1972). Highest densities have been recorded in soft mud sediments (Winston and Anderson, 1970; Schafer, 1972).

The establishment of the burrow begins at the surface when the worm burrows downwards for 8 to 10 cm., then turns and digs upwards to the surface. The walls are mucous-lined. Side tunnels, which are also connected to the surface, are then established and a complex burrow system is constructed. Oxygenated water is brought down the tube by the movements of the parapodia and the dors-ventral undulating movements of the body while breathing (Schafer, 1972). The burrow of Nereis virens is not a feeding structure, but serves instead as a dwelling. Feeding is conducted on the surface as the work actively sifts the sediment.

Nereis therefore affects the host sediment in a number of ways: bioturbation resulting from the creation of permanent burrows; aeration of the upper 20 cm. of sediment due to the active pumping of oxygenated water throughout the burrow complex; active sorting of surface muds while feeding; and biodeposition of ingested mud in the form of discrete fecal pellets.

In the Strait of Canso Nereis burrows were observed in both Ship Harbour and Pirate Harbour. Densities appeared to be higher in Ship Harbour (estimated densities of 320 per square meter) than in Pirate Harbour (estimated densities of 120 per square meter). Schafer (1972) has observed that populations of Nereis increase with decreasing sand content.

2. Scoloplos armiger

The polychaete Scoloplos armiger (Plate 4-2) belonging to the family Arioiidae, burrows throughout the sediment and does not create a permanent dwelling (Schafer, 1972). The worm rarely rises to the surface and usually inhabits only the top few centimeters of the sediment, ingesting sediment and voiding non-cohesive feces. Although found in a variety of substrates, Scoloplos is most abundant in muds and fine sands. Schafer (1972) points out that the trails created by the worm have little affect on disturbing the sediment.

In the Strait of Canso Scoloplos armiger is found in both Ship Harbour and Pirate Harbour in approximately equal densities (10 to 12 per square meter).

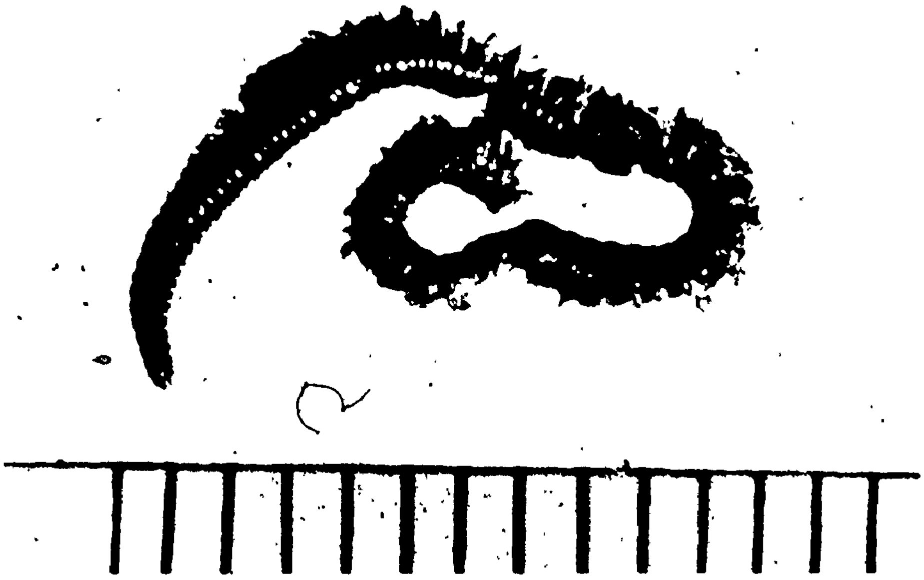


Plate 4-2: Scoloplos armiger from Ship Harbour (scale bar in cm.).

3. Cerebratulus marginatus

The nemertean Cerebratulus marginatus (Plate 4-3) possesses a ribbon-like body which is rounded anteriorly. It is highly contractile, the expanded worm being perhaps ten times its contracted length (Gosner, 1971). Cerebratulus marginatus actively burrows through the sediment, and is found in a multitude of differing substrates. Burrowing is aided by use of the proboscis, which is everted in front of the head and used as an anchor in drawing the body forward (Coe, 1943). Nemerteans are carnivorous and gut analysis conducted by Coe (1943) included protozoa, nematodes, annelids, and larval forms of all phyla of invertebrates.

In the Strait of Canso Cerebratulus marginatus inhabits both Ship Harbour and Pirate Harbour; population densities were impossible to estimate.

4. Astarte undata

The bivalve Astarte undata (Plate 4-4), lies horizontally on one of its symmetric valves (Schafer, 1972). The bivalve has no siphon and its foot is too weak to bury the body in the sediment. Astarte feeds primarily on diatoms and peridineans and is usually found only in sandy areas (Schafer, 1972).

In the study area Astarte undata is found only in Pirate Harbour.

Plate 4-3: Cerebratulus marginatus from Ship Harbour (scale bar in cm.).

Plate 4-4: Astarte undata from Pirate Harbour (scale bar in cm.).

5. *Mercenaria mercenaria*

The bivalve *Mercenaria mercenaria* (Plate 4-5) is a shallow burrowing suspension feeder. The burrowing activity involves the extension of the foot, closure of the siphons, adduction of the shell valves and retraction of the foot (Ansell and Trueman, 1967). The final position reached is dependent on the nature of the substrate and the length of the siphons. *Mercenaria* is usually found in sandy sediment, in areas of slow deposition and minimal turbidity (Rhoads and Young, 1970).

6. *Modiolus modiolus*

The bivalve *Modiolus modiolus* (Plate 4-6) is capable of temporarily attaching itself to hard objects by means of byssal threads. Inanimate objects and shells of living bivalves are used as substrates, especially the shells of members of the same species, and multi-layered colonies can result (Schafer, 19[illegible]2). The valves sit upright, so that both touch the substrate with what is functionally the underside of the animal. *Modiolus* produces a water current to supply itself with breathing water and food; this is accomplished by "whirling" (Schafer, 1972). This same current is used to wash the feces away. *Modiolus* inhabits sandy substrates of low sedimentation rates.

Distribution in the study area is restricted to

Plate 4-5: *Mercenaria mercenaria* from Pirate Harbour (scale bar in cm.).

Plate 4-6: *Modiolus modiolus* from Pirate Harbour (scale bar in cm.).

Pirate Harbour. Wagner (1975) has found Modiolus throughout the Strait of Canso area.

7. Lunatia heros

The moon snail Lunatia heros (Plate 4-7) is a predatory gastropod. Lunatia burrows through the sediment in search of burrowing bivalves, on which it feeds. While Lunatia drills into its prey, it expels white, spindle-shaped feces consisting of drilling mud which is scraped from the calcareous shell of the victim (Zeigelmeier, 1954). Many specimens of Mercenaria were found with boreholes (Plate 4-5) attributed to Lunatia.

The moon snail was restricted to areas in which burrowing bivalves are found and thus are absent from Ship Harbour. Extensive trail systems are produced by Lunatia on the surface and to depths of a few centimeters and can be considered to be effective surface bioturbation agents.

8. Crangon septemspinosa

The caridean shrimp Crangon septemspinosa (Plate 4-8) is a common element of the bottom fauna. The shrimp is ash-grey with numerous irregular stellate, and blackish-brown spots (Williams, 1965). Body lengths vary from 25 to 60 mm. Crangon usually lies on the bottom and buries itself by pushing sediment over its body using its long antennae. According to Price (1962), Crangon septemspinosa is abundant

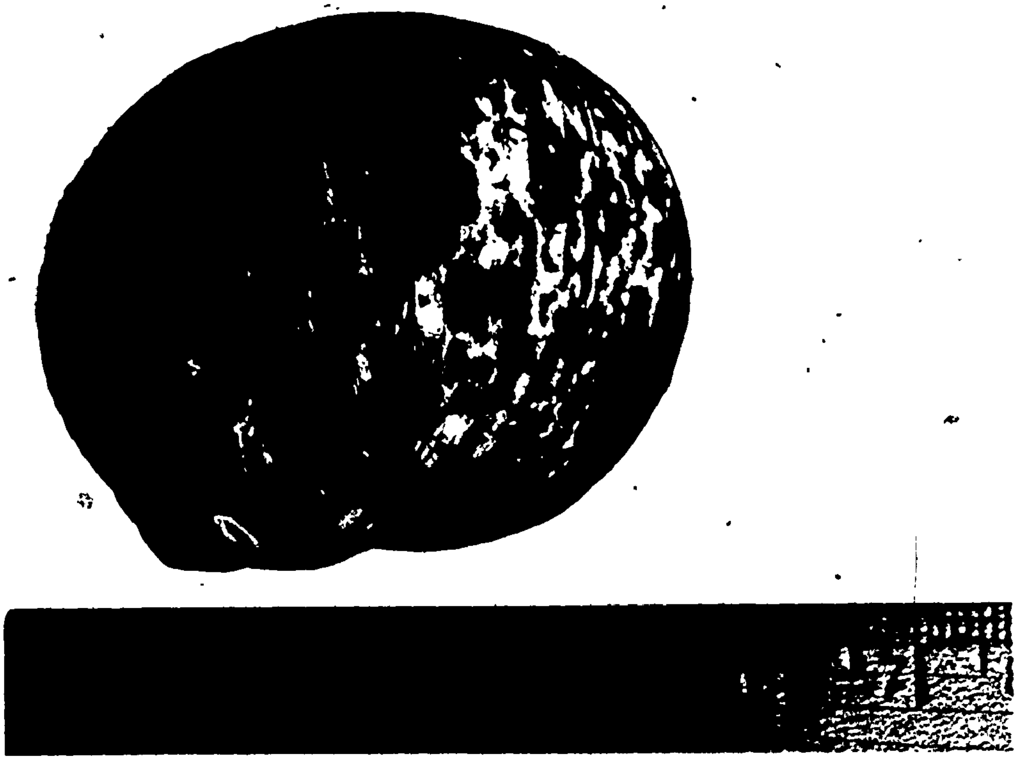


Plate 4-7: Lunatia heros from Pirate Harbour (scale bar in cm.).

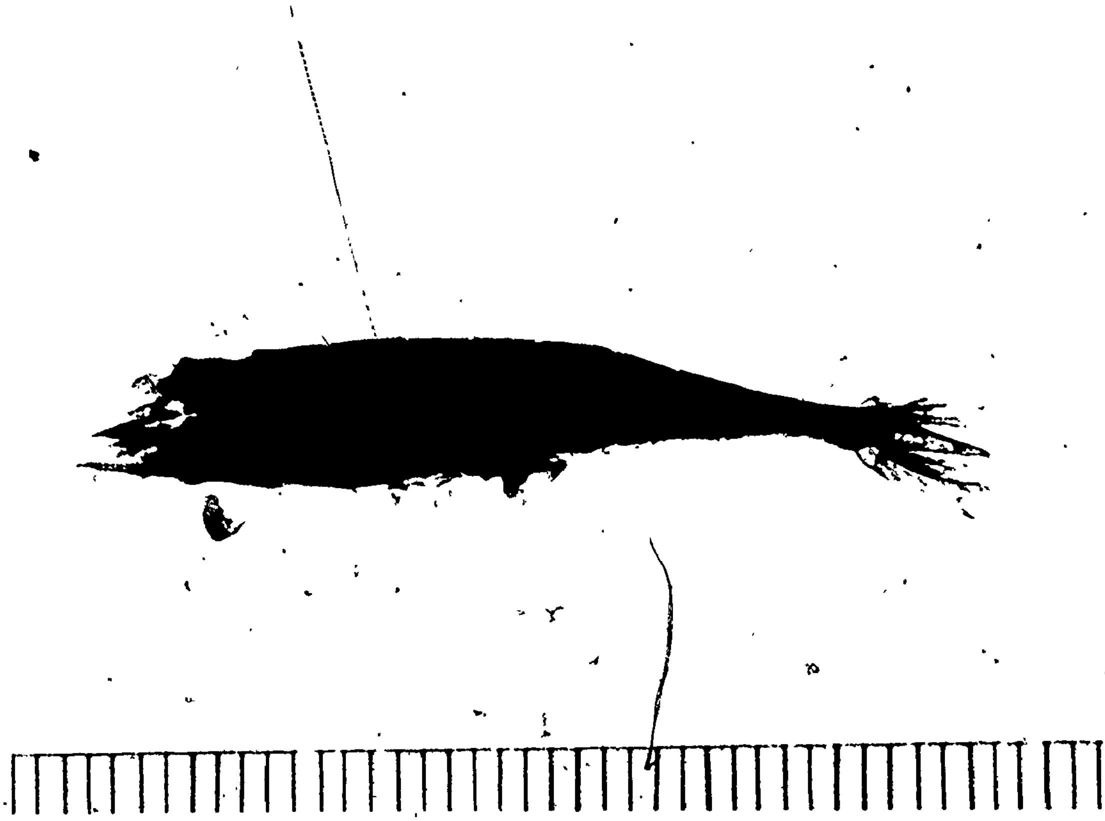


Plate 4-8: Crangon septemspinosa from Ship Harbour (scale bar in cm.).

throughout the region extending from Baffin Bay to Eastern Florida, in depths of water ranging to 450 meters over a variety of bottom types. Gut analysis conducted by Price (1962) revealed that Crangon feeds primarily on polychaetes, Mysidacea, invertebrate eggs and isopods and can be classified as a secondary consumer.

Crangon septemspinosa was found in all areas investigated in the Strait of Canso, and no substrate restriction was noted.

9. Homarus americanus

The American lobster, Homarus americanus (Plate 4-9) belonging to the family Nephropsidae, is one of the most important commercial organisms on the east coast. The lobster is a glossy dark or blueish-green with a reddish-orange background which shows in varying intensities at the edges of legs and claws (Squires, 1965). It is found in the west Atlantic from North Carolina to the Strait of Belle Isle, in depths from a few meters to about 50 m. in coastal areas. Homarus is primarily a sedentary animal and usually occupies depressions which it excavates in the bottom. These depressions remain even after the animal dies and numerous pits dot the bottom surface. The stomach of lobsters studied by Squires (1965) contained the following: Littorina sp., Cancer irroratus, fish bones, polychaete remains, hermit

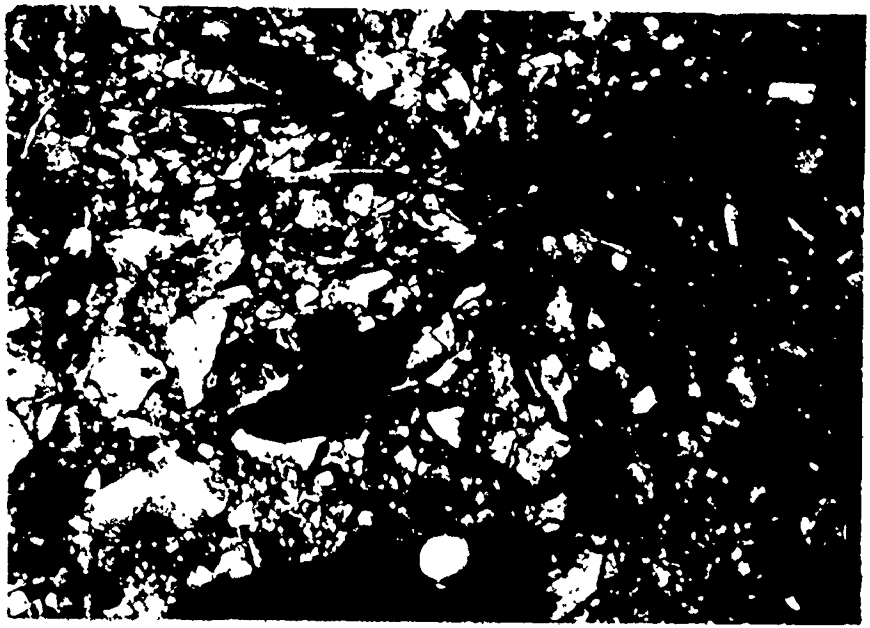


Plate 4-9: Homarus americanus from Pirate Harbour.

crabs, small bivalve shells, and sea stars.

Few lobsters were observed south of the causeway. Discussions with local fishermen revealed that lobster catches had fallen drastically since the advent of industrial growth in the Port Hawkesbury area, although a cause and effect relationship has not been proven.

10. Cancer irroratus

The brachyuran crab, Cancer irroratus (Plate 4-10), belonging to the family Canceridae, is a common element of the benthic fauna. The convex, granulated carapace is approximately two-thirds as long as it is wide. The antero-lateral border is divided into 9 teeth with margins granulated, not denticulate as in Cancer borealis, and with notches between the teeth continued on the carapace as short, closed fissures giving the teeth a pentagonal character (Williams, 1965). The adult carapace is approximately 65 mm. long and 95 mm. wide and is yellowish with closely dotted purplish-brown spots. Cancer irroratus lives from the low water mark to as deep as 314 fathoms. Gut analysis conducted by Squires (1965) revealed the following: small Littorina, amphipods, Crangon septemspinosa, polychaete remains, and small bivalves.

Distribution of Cancer irroratus in the Strait of Canso closely parallels that of Homarus. No specimens were observed in Ship Harbour.

Plate 4-10: Cancer irroratus from Pirate Harbour.

11. Pagurus acadianus

The hermit crab, Pagurus acadianus (Plate 4-11) has red to brown markings on an off-white or pinkish background. The chelae are similar in appearance, although the left is smaller (Squires, 1965). Pagurus acadianus is found in the west Atlantic from the Strait of Belle Isle to Chesapeake Bay in depths varying from low water to 48 m. The hermit crab occupies the shells of gastropods, in particular Buccinum sp. and Lunatia sp. The food contained in the gut of P. acadianus included: fish feces, crustacean fragments, and foraminiferans (Squires, 1965).

Hermit crabs were observed in all areas investigated in the Strait of Canso. Walking trails produced by P. acadianus are easily obliterated by weak currents or the action of other organisms.

12. Deep Burrowing Fauna

In addition, there exists evidence for a deep burrowing fauna in Pirate Harbour. Siphons identified as those of the bivalve Zyrphaea crispata were found. These are of interest since Zyrphaea was not thought to range this far north. Judging from the size of the siphon, these are the largest Zyrphaea known, as well as the deepest recorded burrowing depth (Fournier, personal communication). Prior to this study, Zyrphaea was not thought to occupy such fine-grained clays and sands.

Plate 4-11: Pagurus acadianus from Pirate Harbour (scale bar in cm.).

13. Dimersal Fish

Many dimersal fish are known to be instrumental in the reworking of bottom sediments (Cook, 1971; Stanley, 1971; Risk and Craig, 1976). Depressions of up to 100 cm. in diameter and up to 5 cm. deep are created by skates (Cook, 1971; Stanley, 1971), flounder (Risk and Craig, 1976) and rays (Frey and Howard, 1969; Stanley, 1971) while resting or feeding. Geometric forms range from oval (flatfish) to triangular (skates and rays). In addition, fin marks have also been observed to be commonly created by these dimersal fish.

The most abundant dimersal fish encountered in the Strait of Canso was the winter flounder, Pseudopleuronectes americanus. While feeding on such organisms as amphipods, isopods, crustaceans and bivalve sipoons, Pseudopleuronectes creates oval depressions up to 6 cm. deep and a sizeable disturbance results. Associated with Pseudopleuronectes is the common skate, Raja, which produces a large triangular depression using its wings and gastric pump. Also observed were fin marks created by two species of sculpins, the short-horn sculpin (Myoxcephalus scorpius), and the long-horn (Myoxcephalus octodecemspinosus). The sculpin commonly lies on the bottom waiting for food to venture near.

In environments such as the Strait of Canso the preservational potential of these fish markings is minimal.

In the fine-grained water-rich sediment of Ship Harbour, feeding pits usually disappear in a matter of a few hours as a result of infilling by sediment flowage. The structures in the sediments of Pirate Harbour that display higher sand contents are more easily preserved and pits remained intact for several days.

D. Discussion

Benthic marine invertebrates are predominantly either suspension feeders or deposit feeders, with the exception of a few species that can do both. Divisions of these feeding types have been based on:

(i) the degree of food selectivity among deposit feeders, and

(ii) the level of feeding above the bottom by suspension feeders (Turpaeva, 1959).

Deposit feeders reach maximum diversity and biomass in fine-grained organic muds. Suspension feeders, however, may be less influenced in their distribution by the types of substratum than by the quantity and quality of the suspended material in the water column (Rhoads and Young, 1970). Many investigators have shown that zones of high diversity and abundance of deposit feeders are usually accompanied by low diversity and biomass of suspension feeders (Sanders, 1960; Parker, 1963; Driscoll, 1967; Rhoads and Young, 1970; Rhoads, 1973).

Recently, Levinton (1974) has summarized the major ecological differences between the deposit feeding and suspension feeding trophic groups. Suspension feeders largely depend upon phytoplankton for their food supply. The phenomena of phytoplankton blooms, the control of patchiness by currents and water mixing effects, and the seasonal succession of phytoplankton species, creates an unpredictable food supply for benthic suspension feeders, which depend on the overlying water column (Levinton, 1974). Thus, the abundance of suspension feeders may fluctuate with time (Coe, 1953; Levinton, 1970, 1972). Population densities of suspension feeders depend upon the physical properties of the sediment (Sanders, 1958; Rhoads and Young, 1970).

Deposit feeding organisms, on the other hand, depend on bacteria and other benthic micro-organisms, as their main food supply (Zobell, 1946; Fenchel, 1970). Bacteria in bottom sediments show little seasonal variation and are related to the properties of the sediment (Oppenheimer, 1960). In addition, the sediment reworking activities and fecal pellet production of deposit feeders homogenizes the sediment (Rhoads and Stanley, 1965; Rhoads and Young, 1970). Therefore, deposit feeders show a uniformity in community composition and structure, abundance being related to food availability (Sanders, 1958, 1960; Newell, 1965).

Intensive near-surface reworking by infaunal deposit feeders has been shown to produce a number of changes in sediments dominated by this trophic group:

(i) a semi-fluid granular surface composed of fecal pellets (Rhoads and Young, 1970);
(ii) a surface of biogenic sand-size particles of low bulk density (Rhoads and Young, 1970; Thayer, 1975);
(iii) water contents greater than 80% at the surface (Chapman, 1949; Rhoads, 1970);
(iv) high turbidity at the sediment-water interface (Rhoads and Young, 1970; Rhoads, 1973).

Rhoads and Young (1970) suggested that the physical instability of the reworked surface inhibits suspension feeding benthos by:

(i) clogging filtering structures;
(ii) resuspending and burying newly settled larvae;
(iii) discouraging the settlement of suspension feeding larvae;
(iv) limiting the ability of sessile epifauna to maintain a firm connection with the unstable bottom.

Trophic group amensalism, based on the distribution of the major organisms exists in the Strait of Canso. The two sub-areas fall into the classification proposed by

Rhoads and Young (1970), based on biologic and sedimentologic features. Ship Harbour may be classified as a homogeneous deposit feeder trophic group. This group results when suspension feeders are largely excluded from the deposit feeder biotope by frequent resuspension of biogenically reworked sediments containing fine particles. Rhoads and Young (1970) suggest that this sediment instability and water turbidity is limiting for most suspension feeders. The Ship Harbour community is devoid of any suspension feeding organisms.

Pirate Harbour may be classified as a mixed trophic group. The occurrence of a diverse suspension feeder population on a muddy bottom reworked by deposit feeders, indicates physical stability of the bottom (Rhoads and Young, 1970). The Pirate Harbour community is composed of both suspension feeders and deposit feeders. Suspension feeders found include Mercenaria mercenaria, Astarte undata, and Modiolus modiolus; major deposit feeders include Axius serratus, Nereis virens and Scoloplos armiger.

As stated earlier, the low bulk density and physical instability of some fine-grained muds produce a hostile environment for many suspension feeding organisms. In addition, the typically high water content of these muds may result in a structurally weak surface. It is of importance to the present study to analyze the effect of sediment instability on the known distribution of invertebrates in the Strait of Canso.

A number of investigators have shown that the distribution of organisms in a given area is related to the water content of the sediments (Chapman, 1949; Harrison and Wass, 1965; Rhoads, 1970; Faas, 1972). Sediment containing more than 75% water (weight water/weight of wet sediment) is permanently fluid. In addition, clay-rich muds with 50% to 75% water are thixotropic and become fluid when mechanically disturbed (Boswell, 1961). In such fluid or thixotropic sediments, the bulk density of the individual organisms becomes the limiting factor for successful colonization, because if the organism is more dense than the sediment it will sink (Thayer, 1975). Since the oxidized zone of the sediment extends only a few centimeters below the surface, invertebrates unable to maintain a stable position at the sediment-water interface may sink below the oxidized zone and perish (Thayer, 1975).

The distribution of <u>Mercenaria mercenaria</u> in the study area will be used to illustrate the effect of sediment stability. The bulk density of <u>Mercenaria mercenaria</u> has been reported to be approximately 1.56 gm/cm^3 (Thayer, 1975). In Ship Harbour, the bulk density of the surface sediments ranges from 1.21 to 1.51 gm/cm^3. <u>Mercenaria</u> would sink in these sediments, until its density is equal to that of the surrounding sediment. In the top 20 cm. of sediment in Ship Harbour, the highest bulk density is 1.53 gm/cm^3. *Mercenaria* would thus sink deeper than this depth, which would not permit respiration or feeding at the surface. No specimens of *Mercenaria mercenaria* were obtained in Ship Harbour.

The bulk density of the surface sediments of Pirate Harbour ranges from 1.42 to 1.57 gm/cm^3. This indicates that certain areas in Pirate Harbour are sufficiently dense for *Mercenaria mercenaria* to resist sinking. *Mercenaria* in Pirate Harbour were found only in areas of low density of *Axius* burrows. Analysis of the bulk density data (see discussion in Chapter 6) indicates that bulk density increases with increasing distance from the *Axius* burrow. The highest bulk densities (1.57 gm/cm^3) were located along the fringes of the dense zones of *Axius* burrows. This indicates that the sediment adjacent to *Axius serratus* burrows are structurally too weak to maintain a *Mercenaria* population. North of the causeway, *Axius* is absent and *Mercenaria* is abundant and uniformly distributed.

CHAPTER FIVE

THE OPHIOMORPHA QUESTION

A. Crustacean Trace Fossils

Extensive work has been done on the relationships of various ichnogenera to thalassinid decapods. One of the earliest studies (Weimer and Hoyt, 1964) attributed the creation of the trace fossil Ophiomorpha nodosa to the ghost shrimp Callianassa major. Since then a voluminous literature has accumulated on the burrows of fossoral shrimp or shrimp-like crustaceans, both fossil and recent. Several trace fossil names are now used (Table 5-1) to designate these ancient burrows. The ichnogenera Ophiomorpha, Thalassinoides, and Spongeliomorpha, have in particular received considerable attention. Extensive synonymy lists and bibliographies are found in Kennedy (1967) and Kennedy and MacDougall (1969).

Ophiomorpha Lundregen is a three-dimensional tunnel system that branches dichotomously at acute angles, and is swollen at the point of branching. The circular tunnels are internally smooth, sometimes filled or lined with ovid pellets, when the surface of the filling is mammillated (Kennedy and MacDougall, 1969). This lining cement has been

Table 5-1: Selected References on Fossil Thalassinid Crustacean Burrows

Ichnogenus	Geologic Age	Formation or Series	Location of Study	References
Ophiomorpha	Permian	Cedar Mesa Form.	Utah, U.S.A.	Chamberlain & Baer, 1973.
	Cretaceous	-	Western Interior U.S.A.	Weimer & Hoyt, 1964 Hoyt & Weimer, 1965 Frey & Howard, 1970
		English Town Form.	Delaware, U.S.A.	Pickett, Kraft & Smith, 1971
		Point Loma Form.	California, U.S.A.	Kern & Warme, 1974
		Weald Clay Form.	England	Kennedy & Macdougall 1969
	Paleocene	Woolwich Bottom Bed	Kent, England	Kennedy & Sellwood, 1970
	Eocene	Tallanatta Form.	Mississippi, U.S.A.	Hester & Pryor, 1972
		-	Victoria, Australia	Glaessner, 1948
	Miocene	-	South Poland	Radwanski, 1970
Thalassinoides	Jurassic	Scarborough Form.	Yorkshire, England	Farrow, 1966
		Great Oolite Series	Oxfordshire, England	Kennedy, Jackobson & Johnson, 1969, Sellwood, 1971.

Table 5- l: continued

Ichnogenus	Geologic Age	Formation or Series	Location of Study	References
	Cretaceous	-	North France	Ager & Wallace, 1970
		-	Western Interior, U.S.A	Frey & Howard, 1970
		Niobrara Chalk Form.	Kansas, U.S.A.	Frey, 1970
		Point Loma, Form.	California, U.S.A.	Kern & Warme, 1974
		English Chalk Series	England	Bromley, 1967; Kennedy, 1970
Rhizocorallium	Jurassic	Scarborough Form.	Yorkshire, England	Farrow, 1966
		-	England	Sellwood, 1970
		-	Northern France	Ager & Wallace, 1970
Ardelia	Permian	Cedar Mesa Form.	Utah, U.S.A.	Chamberlain & Baer, 1973
Favreina	Jurassic	-	Middle East	Elliott, 1962
		Great Oolite Series	Oxfordshire, England	Kennedy, Jakobson & Johnson, 1969.
		Great Esturine Series	Inner Hebrides	Scoffin, 1973
	Cretaceous	English Chalk	England	Kennedy, 1970

attributed to collophanite (Weimer and Hoyt, 1964; Pickett et al., 1971), mucous (Rasmussen, 1971), and opaline silica (Hestor and Pryor, 1972). Tunnels range in diameter from 4 to 10 cm. (Kanes, 1963) and may be up to 2 m. in length (Kennedy and Sellwood, 1970).

Thalassinoides is an extensive burrow system with both horizontal and vertical elements. The surface is smooth and branches are at a more or less constant angle of 120 degrees (Kennedy, 1967). Tunnels are generally 2 to 8 cm. in diameter, but swell up to 20 cm. at points of branching. Vertical penetration is usually less than one meter and the tunnels display a semi-circular to circular cross-section (Kennedy, 1967).

Spongeliomorpha is a striated, grooved and branching burrow whose geometry and size is very similar to Ophiomorpha. The striated sculpturing has been attributed to scratch marks or the continual scraping of the walls by appendages as the animal moves against the burrow wall (Kennedy, 1967).

In addition, several other ichnogenera have been attributed to the burrowing activities of thalassinid crustaceans: Ardelia sociala (Chamberlain and Baer, 1973); nodose forms of Gyrolithes (Keij, 1965; Stanton and Warme, 1971; Hestor and Pryor, 1972; Bromley and Frey, 1974); nodose forms of Teichichnus (Hestor and Pryor, 1972; Furisch, 1972); and Rhizocorallium with relatively large outer tubes and wide spreiten and packed with rod-shaped fecal pellets similar to Favreina (fossillized crustacean fecal pellets) (Chamberlain and Baer, 1973).

Recently, there have been opposing views on the taxonomic evaluation of the three main ichnogenera (Ophiomorpha, Thalassinoides and Spongeliomorpha) attributed to thalassinids. Fursich (1973) proposes that all three be lumped into one genera, Spongeliomorpha, because the main morphologic difference is usually the mammillated outer surface of Ophiomorpha, as opposed to smooth walls in Thalassinoides, or walls covered with longitudinal ridges as in Spongeliomorpha. Intermediate forms and forms grading into each other have been recorded by Kemper (1968), Kennedy and MacDougall (1969), Kennedy and Sellwood (1970) and Rasmussen (1971). Mammillated Ophiomorpha, found in sands, may be traced into clays, whereupon they lose the mammillations and become undistinguishable from Thalassinoides (Kemper, 1968; Kennedy and MacDougall, 1969; Kennedy and Sellwood, 1970). Scratch marks, which are the diagnostic feature of Spongeliomorpha, have been described on Thalassinoides (Kennedy, 1967) and Ophiomorphia (Kennedy and MacDougall, 1969).

On the other hand, Bromley and Frey (1974) argue that Fursich's revised taxa are equally as arbitrary and intergradational as the original ones, so that the problem is merely transferred from ichnogenus to ichnospecies level.

The occurrence of combinations of *Ophiomorpha*, *Thalassinoides* and *Spongeliomorpha* as interconnected parts of a single burrow system do not require that these forms represent a single ichnotaxon (Bromley and Frey, 1974). They propose that lumping of the three is not necessary and separation by wall surface is justified.

In the study of trace fossils, several classifications have been used. These range from stratinomic (Seilacher, 1953) to phylogenetic (Seilacher, 1953) to ethologic (Seilacher, 1964). Chamberlain (1971) pointed out that difficulties arise in any system of classification of trace fossils, partly because extensive comparison of morphology and ethology with modern animals has not been made. Trace fossils, for the most part, reflect behaviour of animals and only to a small extent reflect the morphology. In this context, it can be shown that an organism may display more than one behavioural pattern and thus may produce more than one structure. Similarly an organism may display a single behavioural pattern in varying sediments but produce two different traces. To confuse the issue further, different taxa behaving similarly may produce similar structures. Thus, very few ichnogenera can confidently be assigned to existing taxa, and many trace fossils cannot confidently be assigned to ethologic types (Chamberlain, 1971).

Weimer and Hoyt (1964) indicated that *Ophiomorpha* nodosa was constructed by the crustacean Callianassa major, and could be used as an indicator of littoral environments. As a result, there was a concentration of research conducted on the shallow water Callianassa, which led some authors (Heckel, 1965) to imply that the genus was restricted in depth. This view must now be reconsidered since Kern and Warme (1974) have found both Ophiomorpha nodosa and Thalassinoides in rocks that were deposited in a bathyal environment. Since Callianassa major seems to be limited in its tolerance to depth, it seems likely that some other thalassinid crustacean, of deeper water habitat, may be responsible for these structures. Rasmussen (1971) describes burrows in Denmark as resembling Thalassinoides and attributes them to the deep water thalassinid crustacean Ctenocheles.

Reports of modern subtidal thalassinids are extremely rare. Chapman and Rice (1971) observed burrows attributed to Calocaris macandreae in Loch Torridon, Scotland, in water depths of up to 30 meters. Buchanan (1963) reported on Calocaris from off the coast of Northumberland, as being restricted to water depths of 30 meters or more. Whiteaves (1874) dredged a sample of Calocaris from 360 meters in the Gulf of St. Lawrence. Subtidal specimens of Callianassa have been reported from depths of 500 meters off California (Stevens, 1921), and from 600 meters off Florida (Biffar, 1971). In addition, the thalassinid Thalassina anomala constructs burrows similar to Callianassa major in estuarine sediments (Pearse, 1911; Sankolli, 1963).

Studies on modern environments, from varying depths (Shinn, 1968; Farrow, 1971; Frey and Mayou, 1971; Hertwick, 1972), indicate that several different callianassids produce burrows which exhibit branching patterns and wall structure similar to Ophiomorpha and Thalassinoides. In addition, it has been shown that other crustaceans construct similar burrows: glypheoid shrimps (Sellwood, 1971; Bromley and Asgaard, 1972); alpheid shrimps (Shinn, 1968; Farrow, 1971); stomatopods (Frey and Howard, 1969; Hertwick, 1972; Braithwaite and Talbot, 1972); astecid lobsters (Rice and Chapman, 1971); and even brachyuran crabs (Chamberlain, 1975).

B. Description of Casts

Polyester resin casts of burrows attributed to the thalassinid crustacean Axius serratus were recovered in water depths ranging from 9 to 10.5 m., in the Strait of Canso. Buckley et al. (1974) captured a specimen of the shrimp from a core that was taken in water 40 m. deep. These casts are similar in geometry and surface ornamentation to several ichnogenera thought to be produced by thalassinids. Casts were recovered from two sites within the Strait, Ship Harbour and Pirate Harbour, and displayed marked differences in morphologic characteristics (see previous discussion on

Plate 5-1: Polyester resin cast (C-3) of Axius burrow from Ship Harbour.

Plate 5-2: Polyester resin cast (C-5) of Axius burrow from Ship Harbour.

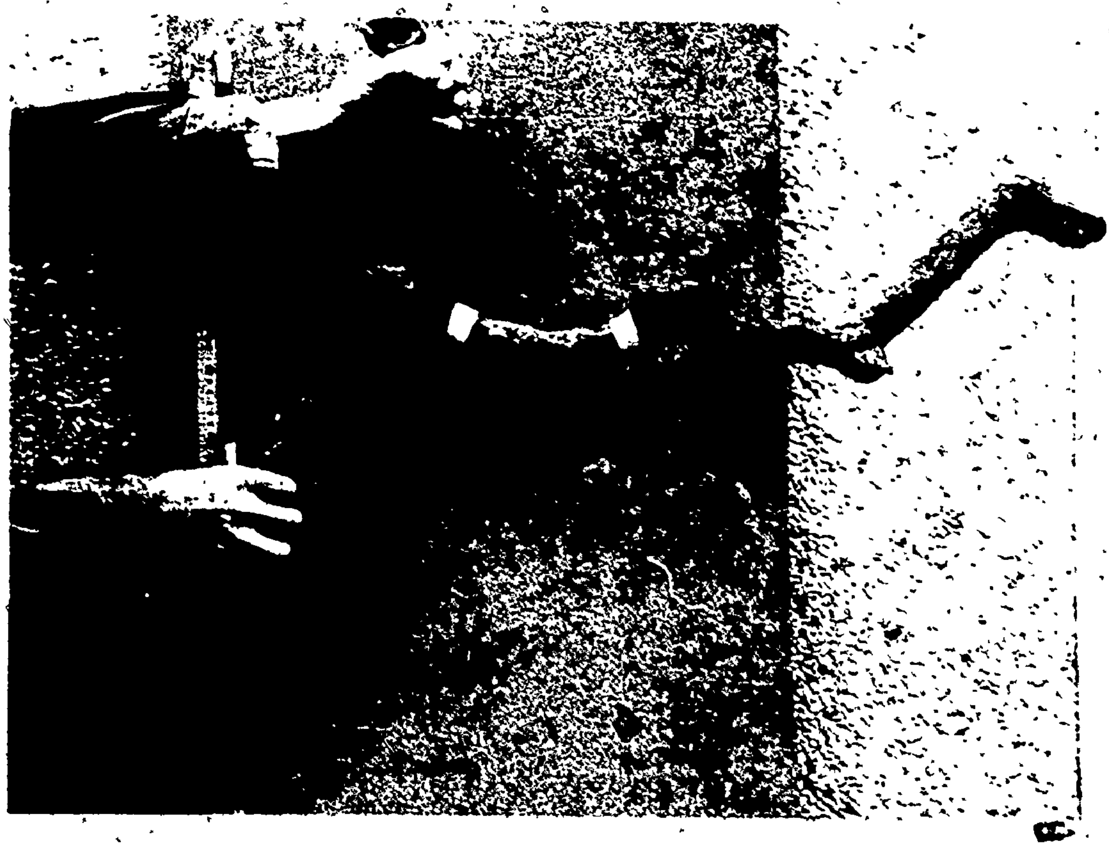


Plate 5-3: Polyester resin cast (C-1) of *Axius* burrow from Ship Harbour.

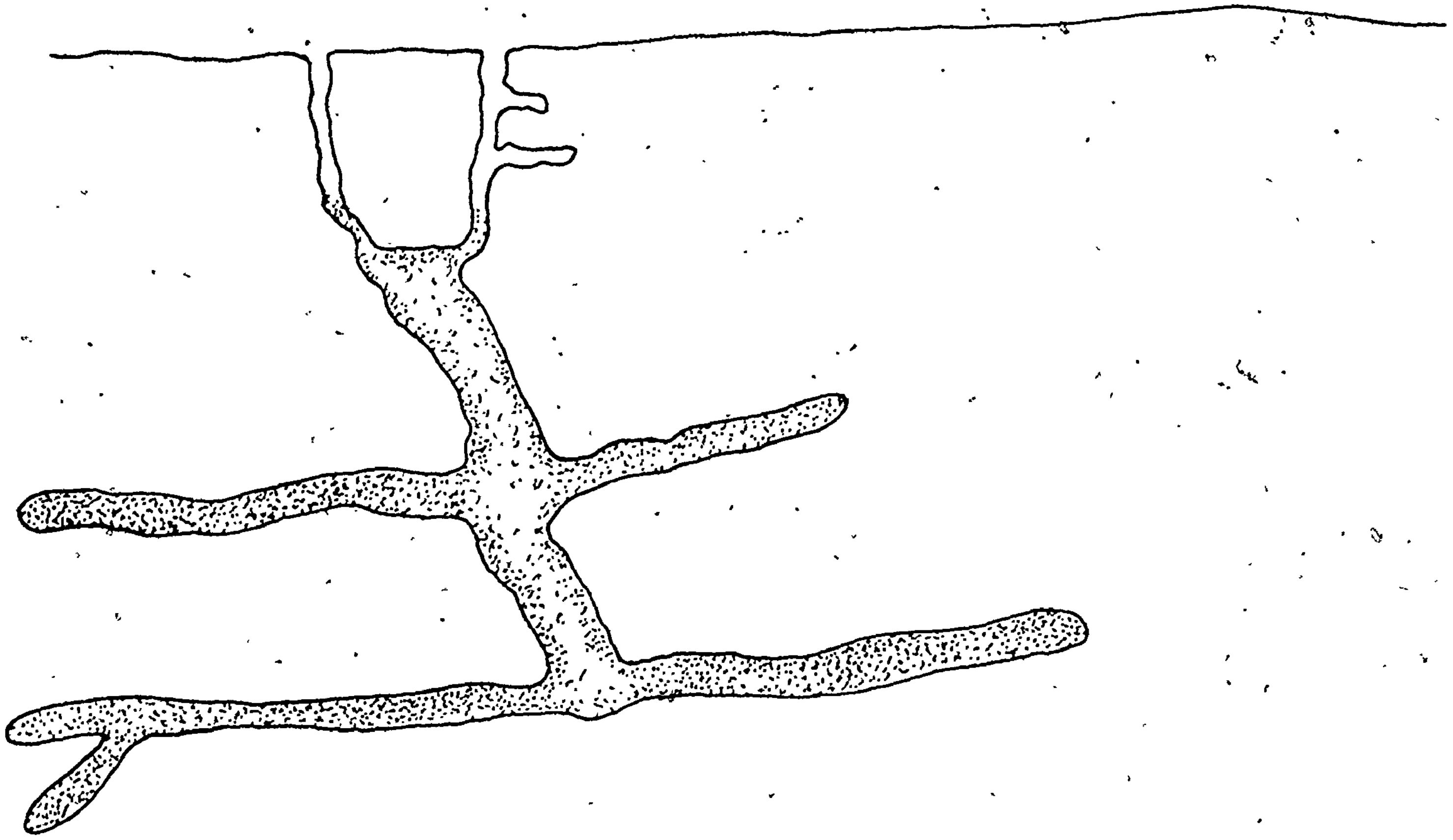


Fig. 5-1. Composite reconstruction of Ardelia socialia.

burrow morphologies).

In Ship Harbour, the polyester resin casts (Plates 5-1, 5-2, 5-3) show marked affinities to the trace fossils Ophiomorpha and Ardelia. Geometric configurations closely approximate those of the genus Ardelia (Figure 5-1). Ardelia is a relatively new ichnogenus described from Permian strata in Utah by Chamberlain and Baer (1973). It is associated with Ophiomorpha and is thought to be the earliest known occurrence of thalassinid burrows. Ardelia consists of large horizontal sandstone cylinders and rods joined by vertical and/or oblique elements. The surface is relatively smooth but varies locally from irregular to nodose. Diameters range from 5 to 20 cm.; lengths vary from 30 cm. to 2 m. (Chamberlain and Baer, 1973). The structure exhibits bifurcations from central chambers. Cast C-5 (Plate 5-1) is very similar to Ardelia (Figure 5-1) in both size, shape and surface ornamentation.

Diagnostic features of Ophiomorpha are also exhibited by the polyester resin casts from Ship Harbour. Analysis of the major ichnogenera suggests that both Spongeliomorpha and Thalassinoides are mainly horizontal burrow complexes (Kennedy, 1967; Fursich, 1973), while Ophiomorpha consists of both horizontal and vertical complexes (Kennedy and MacDougall, 1969), or mainly vertical elements (Seidel, 1956; Hillmer, 1963). Plate 5-1 illustrates that the burrows of

Axius serratus may be considered to be mainly vertical in orientation. Perhaps the most diagnostic feature exhibited by Ophiomorpha is the knobby surface ornamentation (Figure 5-2), which has been attributed to a fecal pellet lining system, used to strengthen the burrow walls in shifting sand environments (Weimer and Hoyt, 1964; Hoyt and Weimer, 1965). This surface feature may be seen on the resin casts (Figure 5-3-2). Kennedy and MacDougall (1969) illustrated Ophiomorpha burrows in the Weald clay of England which extended vertically downward for 1.5 m. and displayed meniscus-like fillings along their vertical elements. Similar features can be seen on the vertical shafts of the casts of Axius serratus burrows (Figure 5-3-1).

The resin casts recovered from Pirate Harbour (Plate 5-4) are very different from those of Ship Harbour. The cast is circular in cross-section, displays smaller diameters and is unlined. Similar features include the presence of chambers and bifurcations at these chambers. Axius burrows in Pirate Harbour more closely resemble the ichnogenus Thalassinoides. The cast from Pirate Harbour was unfortunately broken during recovery, but Plate 5-4 illustrates the initiation of horizontal branching. It is not known at this time, however, if the burrow extended any deeper.

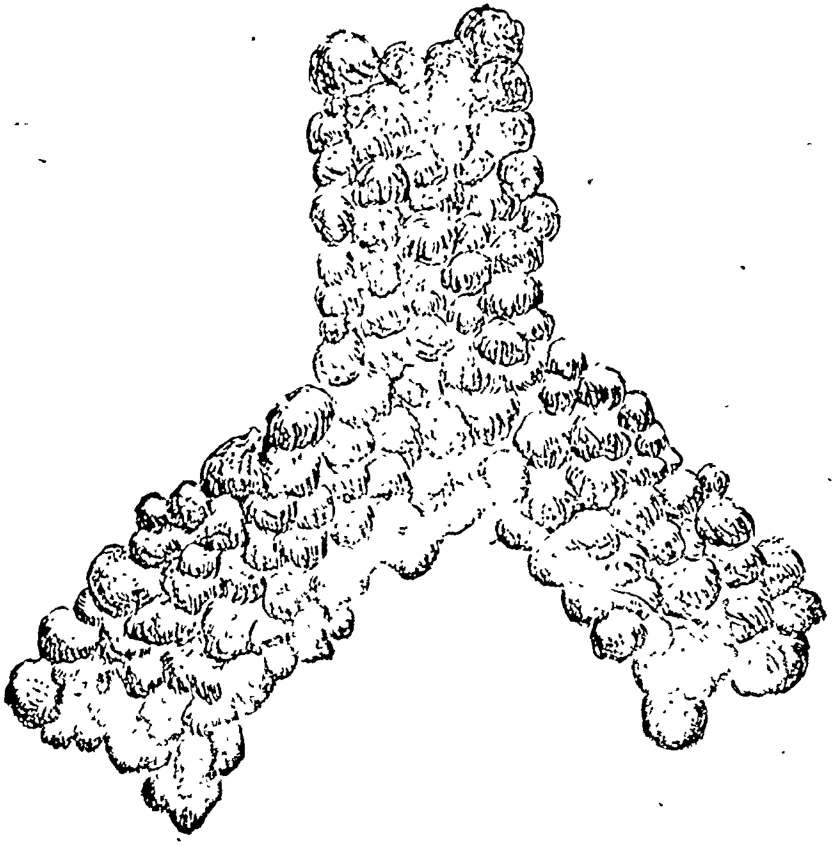
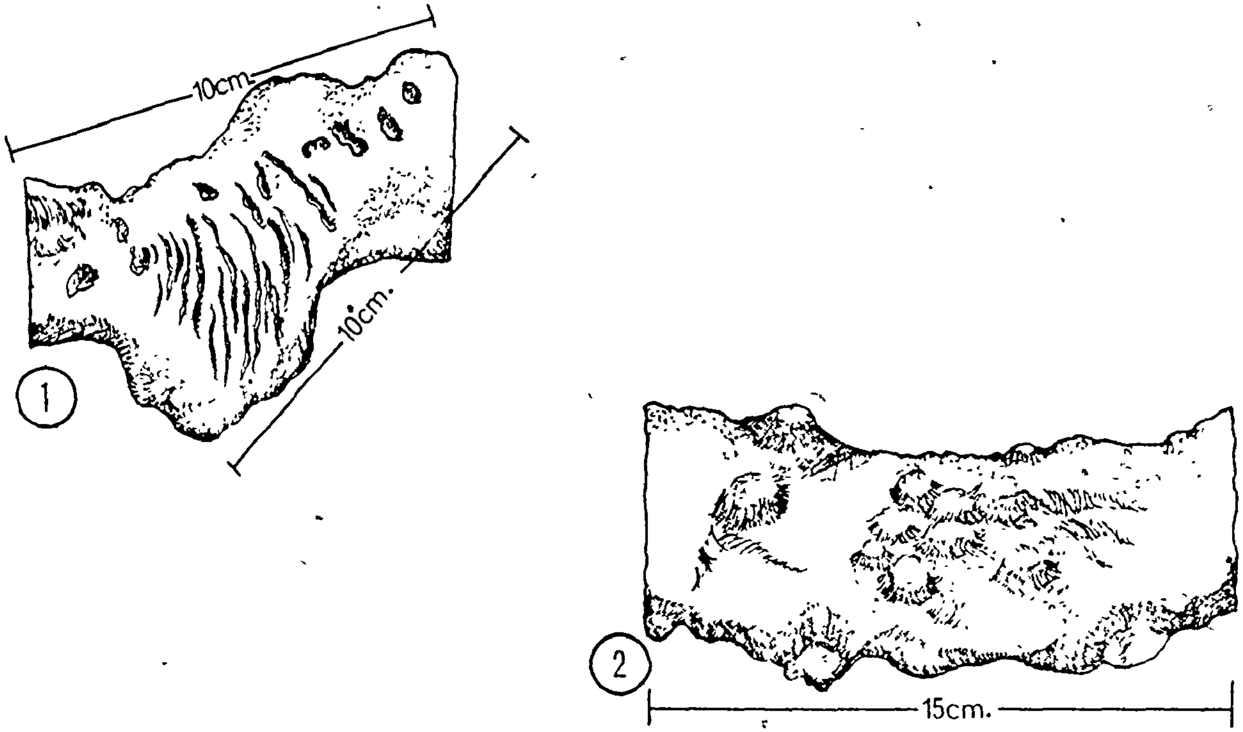


Fig. 5-2: Exterior of *Ophiomorpha nodosa* (from Weimer and Hoyt, 1964)



1"(inch)=5cm.

Fig. 5-3: 1) Laminations on flocr of Cast C-1

2) Bumpy, knob-like outer surface of Cast C-1

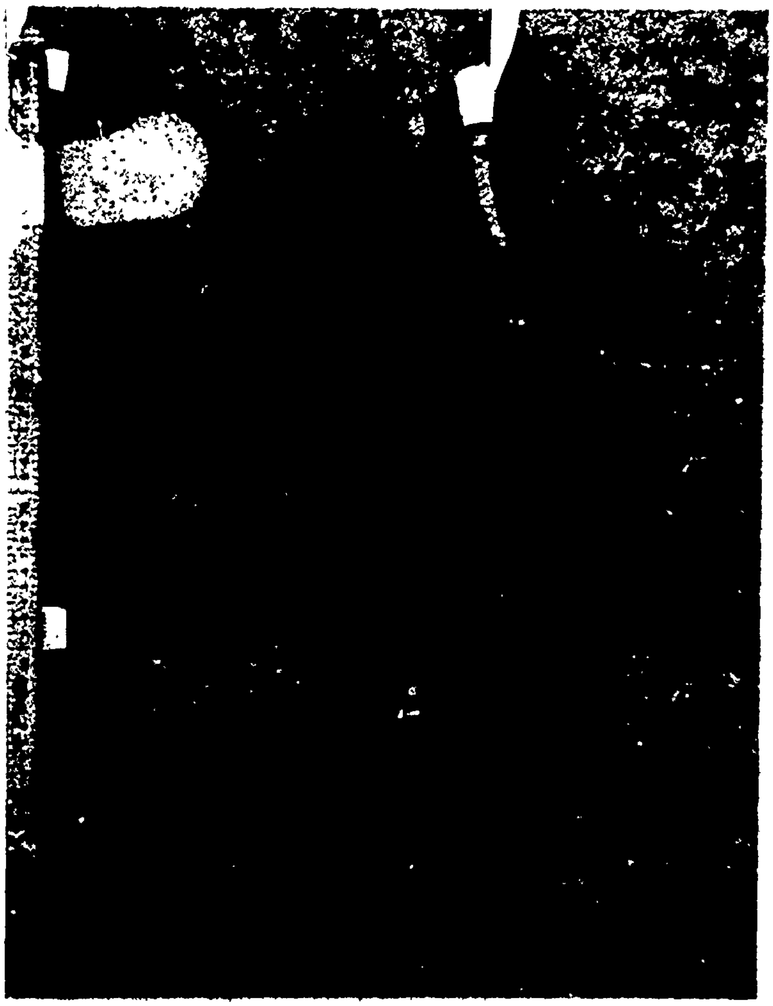


Plate 5-4: Polyester resin cast of Axius burrow from Pirate Harbour.

C. Discussion

In the two most recent papers on the taxonomic evaluation of thalassinid ichnogenera, both Furisch (1973) and Bromley and Frey (1974) stressed the importance of wall structure in their identification. In light of the continued interest in the ethological classification of ichnofossils proposed by Seilacher (1964), and refined by a host of others (see Simpson, 1976, for review), the morphologic variations in wall structure are of utmost importance and the system proposed by Bromley and Frey (1974) seems justifiable.

Bromley and Frey (1974) point out that in any system of burrows morphological variation is the result of several factors:

(i) the wide variety of organisms responsible for such burrows;
(ii) the diversity of environments, in which the burrows are preserved;
(iii) the difference in behavioural patterns regulating the burrow activity;
(iv) the differences in the processes or circumstances of preservation.

Thus, variations stem not only from phylogeny and major habitat adaptations, but also from differences in burrowing techniques in relation to changes in the immediate environment. The prominence and construction of crustacean burrow walls are commonly influenced by coherence of the substrate. It has been shown that Ophiomorpha loses the knobby surface texture with increasing depth, which may be an indication of more stable sediment at greater depths of burial (Kennedy and Sellwood, 1970; Frey, 1971). Frey and Howard (1972) illustrated that Callianassa major does not construct thick knobby walls in the quiet water and stable substrates of an aquarium. In their investigation of the ichnofauna of the Point Loma Formation, Kern and Warme (1974) found specimens of knobby exterior Ophiomorpha from sandstone beds, interconnected to unlined, smooth walled Thalassinoides in mudstone beds. They concluded that the system was clearly produced by the same animal.

The variations of morphology of the burrows constructed by Axius serratus in the Strait of Canso may also reflect differences in the substrate. The differing mass physical properties of the two areas studied (see Chapter 6 for discussion) may account for changes in the burrowing of the shrimp. Sediments in Ship Harbour, because of their unstable nature, afford the shrimp little resistance in burrowing and may necessitate the creation of linings to enable the system to remain open. This may perhaps be similar to Callianassa lining its burrow in a shifting sand environment, as illustrated by Shinn (1968). On the other hand, the sediments of Pirate Harbour are more cohesive and exhibit reserve strength characteristics (Brown and Rashid, 1976) which may impede burrowing and eliminate the need for any linings.

In summary, it should be stressed that ichnogenera such as Ophiomorpha, which in the past has been viewed as a shoreline indicator, cannot be associated with one specific organism (such as Callianassa major). Structures similar to this ichnogenera have been created by the subtidal thalassinid Axius serratus. Trace fossils of this type may prove even more significant when viewed in a sedimentological sense. Various mass physical properties could be inferred (see Rhoads, 1974). Local variations in the morphology of the burrows may reflect changes in: sediment stability; grain size distribution; depth of burial; sedimentation rate; and water content.

CHAPTER SIX

EFFECT OF AXIUS ON THE MASS PHYSICAL PROPERTIES

A. Introduction

Mass properties of fine-grained clastic sediments depend on a number of characteristics: specific gravity of the grains, grain size distribution, clay mineralogy, water content, void ratio and degree of saturation (Harrison et al., 1964). These mass properties may be subdivided, from a geological point of view, into those that are dependent almost exclusively upon the source and depositional environment of the sediment (primary properties); those that depend mainly upon the post-depositional history of the deposit (secondary properties); and those that are affected considerably by both factors (intermediate properties) (Rominger and Rutledge, 1952). These properties are summarized in Table 6-1.

Investigations by Moore (1961), Harrison et al. (1964), Richards (1964), Miller and Richards (1969) and Inderbitzen (1970) have all stressed the way in which various properties affect the mass properties of a sediment. Little work has been done on the effect of organisms on the mass properties of sediments, although a few studies have been

Table 6-1: Types of mass and related physical properties (Harrison et al. 1964)

Primary Properties (Dependent on source and depositional conditions)	Intermediate Properties (Dependent on both original sediment and environmental effects)	Secondary Properties (Dependent on post depositional environmental effects, especially stress history)	Related Physical Properties
Atterberg plasticity limits Liquid Limit Plastic limit Plasticity index	Shear strength (cohesion Mass unit weight Bulk chemical composition Colour Sensitivity	Liquidity Index Preconsolidation stress	Specific gravity of grains Grain size distribution Sediment sorting Clay mineralogy Natural water content Degree of saturation Gas content Temperature

published (Chapman, 1949; Harrison and Wass, 1905; Rhoads, 1970, 1975).

Rhoads (1970) has shown that the vertical distribution of infaunal deposit feeders controls the sediment water content. Relatively thick, fecal-rich upper zones are produced by certain organisms: the bivalves Nucula proxima and Macoma tenta (Rhoads and Young, 1970); Yoldia limatula (Rhoads, 1963); and the holothurian Molpadia oolitica (Rhoads and Young, 1971). These near-surface zones exceed 60% water content and may appraoch 80% (per cent wet weight) in highly reworked areas (Rhoads, 1970). Chapman (1949) illustrated that muddy sediments which exhibit large water content values have a tendency to display a thixotropic nature. Boswell (1961) links this to the transformation gel/more fluid-gel/gel, which for a muddy sediment gives it the tendency to flow (Figure 6-1). The physical state of a sediment of fixed solid composition (clay-silt-sand) is thus directly related to water content, a parameter influenced by burrowing activity. High clay content muds containing greater than 50% water (per cent wet weight) display false-bodied thixotrophism or fluid properties.

B. Sampling Procedures

The major portion of the field work consisted of the establishment of transects running horizontally away from a main burrow opening. Undisturbed sediment samples were

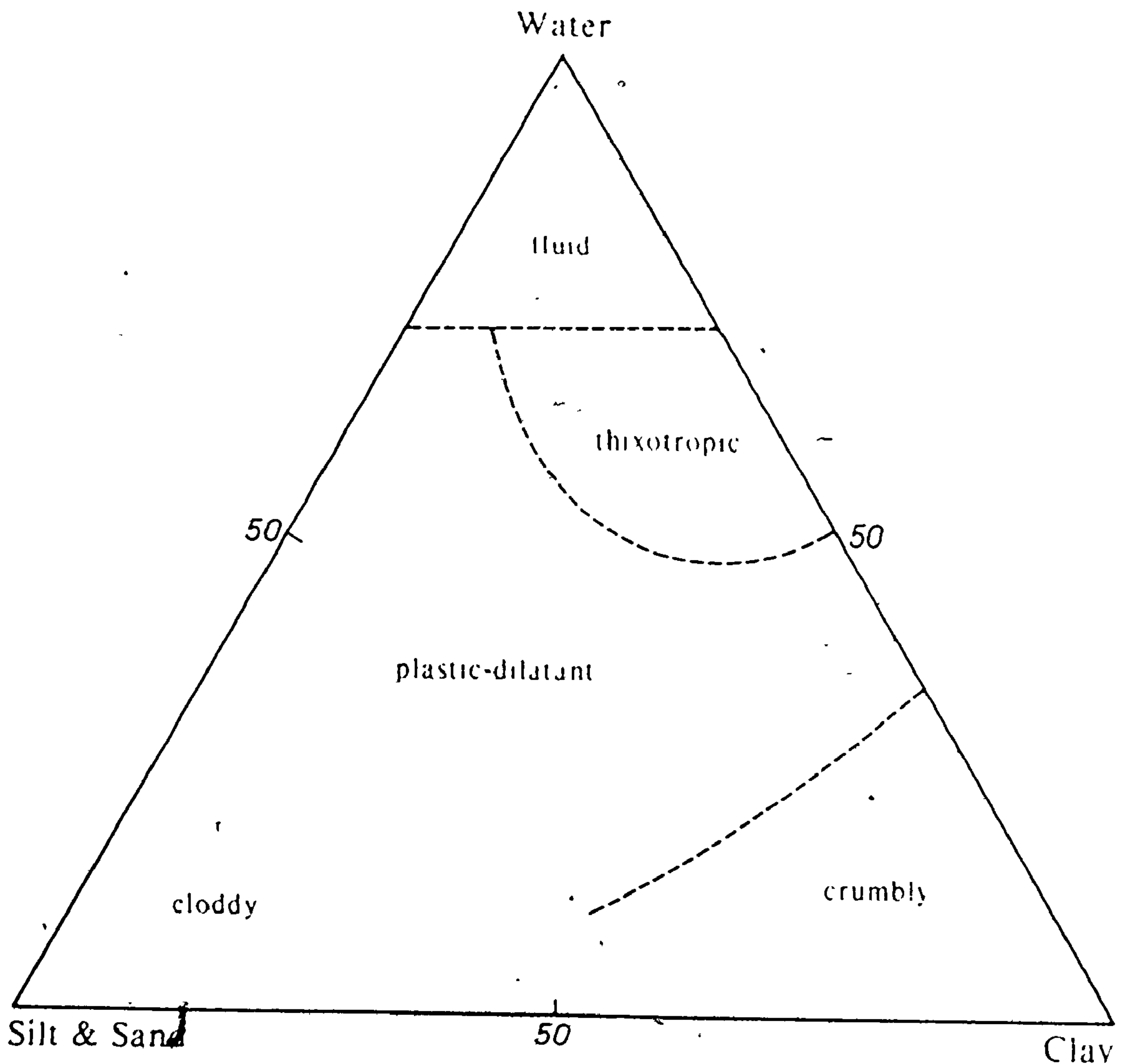


Fig. 6-I: Mass properties of sediments related to grain-size and water content (after Boswell, I96I).

obtained at regular intervals (30 cm.) along the transects, using SCUBA and short (15 cm.) plastic core barrels (5 cm. I.D.). These cores were then frozen as soon after collection as possible for subsequent study in the laboratory. The use of <u>in situ</u> sediment collection was employed since many mechanical samplers partially displace the liquid surface layer (Rosefelder and Marshall, 1970; Vilks <u>et al</u>., 1975).

In addition, sediment samples for determination of physical properties were obtained using constant volume plastic containers.

C. Analytical Procedures

The mass properties commonly studied by the marine geologist and measured during the course of this study are summarized in Table 6-2.

1. Water Content

The determination of water content follows the standard ASTM (1971), Designation D2216-66, test. There was no correction for salt content. Frozen samples were weighed, placed in an oven for 24 hours at 105°C, and reweighed. The water content (w) was then calculated as a per cent dry weight using the formulae:

$$w = \frac{W - W_s}{W_s} \times 100$$

Table 6-2: Geotechnical Test Procedures

Property	Test Procedure & Reference	Modifications & Notes
Grain size	Folk (1974	Sample not dried prior to testing.
Water Content	ASTM (1971), Designation D2216-66	No correction for salt content.
Liquid Limit	ASTM (1971) Designation D423-66	Sample not dried or sieved prior to testing, no correction for salt content.
Plastic Limit	ASTM (1971) Designation D424-59	Sample not dried or sieved prior to testing, no correction for salt content.
Bulk Density	Richards <u>et al.</u>(1974)	Volume of cylinders
Void Ratio	Lambe (1951)	Unit weight of water used was 1.025 glec., volume of cylinders
Grain Density	Lambe (1951)	Use of temperature-calibrated volumentric flask.
Activity	Skempton (1953)	Clay fraction, is material finer than two microns.

Where W equals the total weight of the sediment mass, and W_s equals the weight of the solid matter.

2. Grain Size

Particle size distributions were assessed for all samples according to the procedure outlined in Folk (1974). Each sample was first treated with ammonium hydroxide to remove any organic material and subsequently washed with distilled water. A dispersion agent, sodium hexametaphosphate, was added and each sample was wet sieved in order to separate the sand from the mud. The material left on the four phi sieve was then dried, disaggregated, weighed and resieved. Any material that passed through the four phi screen was retained and added to the mud fraction obtained from the first sieving. The mud fraction was then analyzed using the pipette method to determine the amounts of the silt and clay fractions.

Designations of sediment types are based on comparative ratios between sand, silt and clay (Shepard, 1954; Blatt et al., 1972; Folk, 1974), where sand is composed of particles greater than 4 phi in diameter, silt is 4-8 phi, and clay is greater than 8 phi. The relative percentages of these three textural grades were determined for each sample by plotting these ratios on a triangular diagram (Figure 6-2).

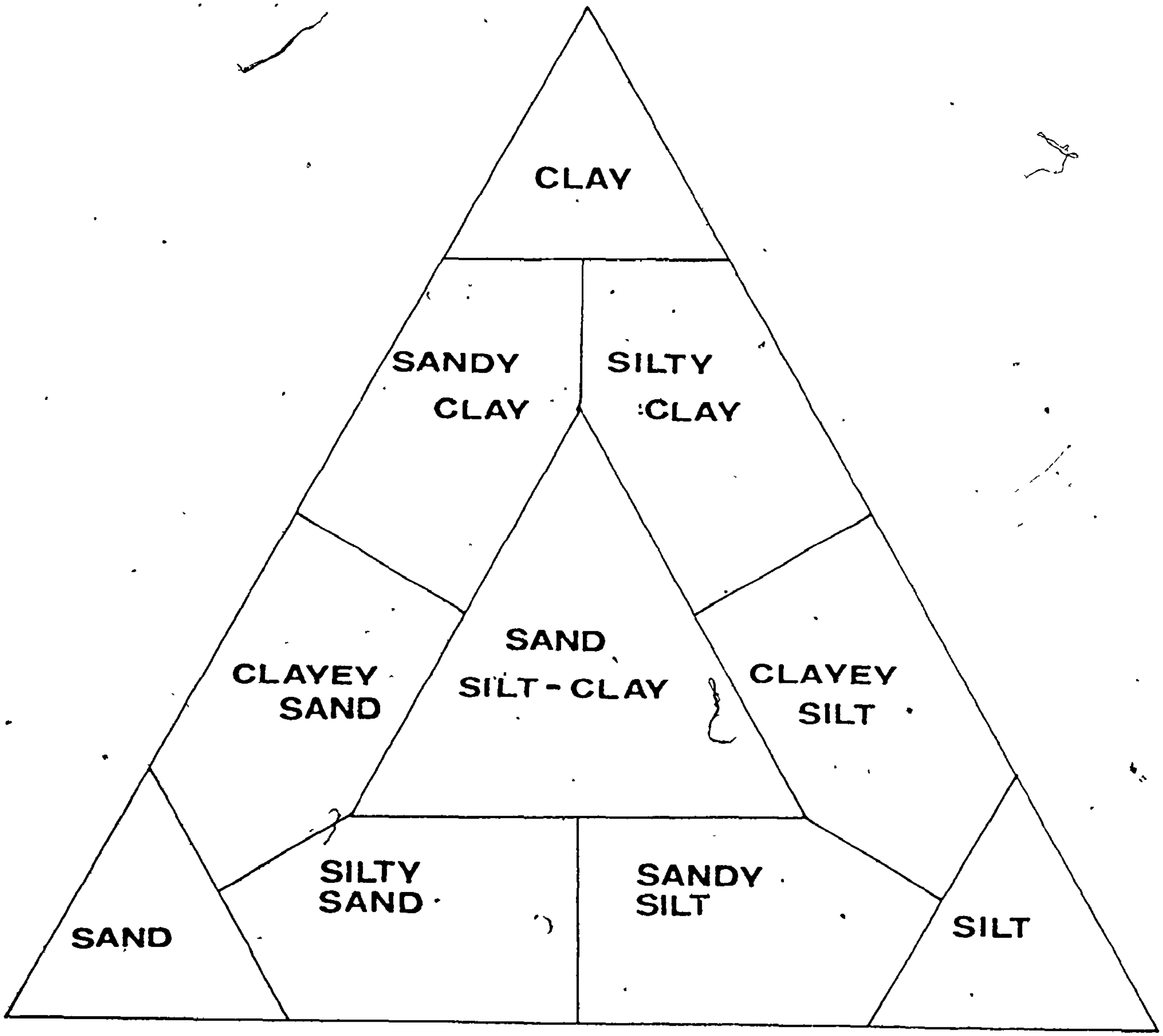


Fig 6-2: Classification of sediments (after Shepard, 1954).

3. Atterberg - Limits and Indices

A sediment exhibits plastic behaviour over a range of water contents from a lower limit to an upper limit. The plastic limit is that water content below which the soil is not plastic when it is worked, and crumbles on application of pressure. At the liquid limit the change is from plastic to flow behaviour. Most present measurements of plasticity and plasticity limits are based on the early work of Atterberg and are often called Atterberg limits (c.f. Baur, 1960). Since only the smaller particles of soils, clays and to some extent silts, exhibit plastic behaviour the standard ASTM (1971) test (Designations D423-66 and D424-59) calls for the samples to be dried and sieved. These testing procedures have been modified to adapt to marine samples. Studies by Richards (1962) and Keller and Bennett (1970) suggest that in the determination of the Atterberg limits the samples should not be dried or sieved prior to testing.

The liquid limit (LL) was determined with a mechanical device which jars the sample in a reproducible way (Casagrande device, Casagrande, 1948). The sediment sample is placed in a brass cup and a groove one half inch in width is made in the sample with a grooving tool. The cup is then repeatedly dropped from a height of one centimeter until the sample flows together in the groove. The liquid limit is defined as the water content at which 25 of the standardized blows are required to close the groove. Below this water content the soil is plastic, and above it begins to exhibit flow properties.

The plastic limit (PL) is measured by rolling a sediment sample into a thread. The water content is adjusted by trial and error to a point where the soil will roll into threads approximately one-eighth inch in diameter before it crumbles. If the water content is too low, crumbling occurs at larger diameters, if it is too high, crumbling will not occur until the diameter is below one-eighth inch. Thus, the plastic limit is both a measure of cohesion of the soil particles and a measure of resistence to cracking when the sample is worked. A plastic material will not crack, while a solid will. Therefore, this point is taken as the lower limit of plasticity of the sample.

At the liquid limit, the sediment particles are separated by water just wide enough to deprive the sample of its shear strength, and the fine sediment particles tend to flow under the influence of gravity (Jumikis, 1962). At the plastic limit, the soil moisture does not separate the soil particles. Here the moisture has enough surface tension to affect contact between sediment particles, causing the soil mass to behave as a semi-solid. The difference in moisture content between liquid and plastic limits is termed the plasticity index (PI):

$$PI = LL - PL$$

Thus, the plasticity index indicates the moisture range through which a cohesive sample has the properties of a plastic material. According to the classification of Atterberg (1911), when the plasticity index exceeds 17, the sample is of high plasticity.

Water content by itself tells little about a sample, but relative to the liquid and plastic limits it is very significant, indicating whether a cohesive sample is in the solid, plastic or liquid state (Jumikis, 1962). The ratio of the difference between the water content and the plastic limit to the plasticity index is referred to as the liquidity index (LI):

$$LI = \frac{W - PL}{PI}$$

The limits of the relative plasticity of a sample thus varies between 0 (the plastic limit) and 1 (the liquid limit). When LI is less than zero, the sample is in a semi-solid or solid state. When the LI value falls between zero and one the sample is in a plastic state; when the LI is greater than one, the sample is in a liquid state.

4. Void Ratio

The ratio of the volume of voids to the volume of solids is designated the void ratio (e). Void ratios were determined in conjunction with known volume samples taken for water content and mass unit weight. If one assumes 100% saturation of the voids with water then:

$$e = \frac{G_s \gamma_w V}{W_s} - 1$$

Where: G_s equals the specific gravity of the solid grains, γ_w equals the unit weight of water (1.025 g/cc), V equals the volume of the sample, and W_w equals the weight of the solid grains (Lambe, 1951).

The per cent of saturation (Sr) of marine sediments is (Richards, 1962):

$$Sr = \frac{W_w}{\gamma_w \quad V - \frac{W_s}{G_s \gamma_w}}$$

Where W_w equals the weight of the water. In this present study, the computed degree of saturation was greater than 95% in all samples, thus it was not used in the determination of the void ratio.

5. Porosity

The porosity (n), is defined as the ratio of void volume to total volume in a sediment, and is found from:

$$n = 1 - \frac{W_s}{G_s \gamma_w V}$$

Similar to void ratio, porosity is a measure of the denseness of a sample. The computation of porosity involves the same measurements as the computation of void ratio and the two are related by:

$$n = \frac{e}{1 + e} \times 100$$

6. Grain Density

The specific gravity (G_s) of the dry solids of a sediment is defined as the ratio of the density (γ_s) of a given volume of the sediment solids to the greatest density of an equal volume of pore water (γ_w). The present study employs the method described in Lambe (1951), which involves use of a temperature-calibrated volumetric flask. In this procedure the specific gravity is determined from:

$$G_s = \frac{W_s G_T}{W_s - W_1 + W_2}$$

Where:

G_T = specific gravity of distilled water at temperature T;
W_s = dry weight of soil;
W_1 = weight of volumetric flask, sample and water;
W_2 = weight of volumetric flask, plus water at temperature T.

Since the specific grain density of a sediment is extremely important in the determination of other properties, more than one test was conducted on each sample. It should also be noted that the value obtained is the average density of all solid constituents contained in the sample.

7. Mass Unit Weight

The saturated mass unit weight (γ) of a sample is defined as the weight of sediment per unit volume (Richards *et al.*, 1974). This assumes that the sediment is at its natural water content and does not contain gas. This assumption is valid for measurements made *in situ* (Richards and Parker, 1968). Mass unit weight was measured by inserting a small, thin-walled right cylinder, of known volume (V), into the sediment mass. The cylinder and sediment are then weighed, subtracting the weight of the cylinder to obtain the weight of the sediment (W), and performing the following calculation:

$$\gamma = W/V$$

8. Activity

The ratio of plasticity index to per cent clay (finer than two microns) is known as the activity of the sample (Skempton, 1953). This represents the surface activity of the clay fraction, such as the increased ion exchange capacity and absorption of water with decreasing grain size. Skempton (1953) proposed a classification of samples based on the activity. Three distinct zones are recognized: active (activities greater than 1.25); normal (activity ranges from 0.75 to 1.25); and inactive (activities less than 0.75).

The activity of samples has been shown to be a function of the mineralogical composition of the clays (Bjerrum, 1954) and the amount of organic matter (Rashid and Brown, 1975).

D. Results

The investigation of the mass physical properties, of the sediment of the Strait of Canso, was limited to Ship Harbour and Pirate Harbour. In the ensuing discussion surface samples refers to sediment at the sediment-water interface; while subsurface samples, refers to sediment at a depth of 20 cm.

1. Distribution of Properties

The mass physical properties previously discussed were analyzed for a number of transects in both Pirate Harbour (Table 6-3) and Ship Harbour (Table 6-4). The transects were established in such a way that samples (both surface and subsurface) were taken at a main burrow opening and then at 30 cm. intervals, in a direction such that no other burrows were encountered. The transect terminated in a sample that could be deemed as unburrowed (by the shrimp). Three transects were established and sampled in both Pirate Harbour (Figures 6-3, 6-4, 6-5) and Ship Harbour (Figures 6-6, 6-7, 6-8).

a. Sediment distribution

The bottom sediments were classified according to the system established by Shepard (1953). Surface sediments (Figure 6-9) and subsurface sediments (Figure 6-10) fall into three main categories: silty clay, clayey silt, and sand-silt-clay. These sediment types conform with those found in earlier investigations of the same area by Buckley _et al_. (1974) and Brown and Rashid (1975).

Bottom sediments in Ship Harbour display higher clay contents, in both surface and subsurface samples, than Pirate Harbour. Mean values for clay content for the 25 samples taken in Ship Harbour were 53% (range: 33-66%),

Figs. 6-3 to 6-8

Fig. 6-3 to 6-5: Transects displaying the distribution of mass physical properties of the surface and subsurface sediments of Pirate Harbour.

Fig. 6-6 to 6-8: Transects displaying the distribution of the mass physical properties of the surface and subsurface sediments of Ship Harbour.

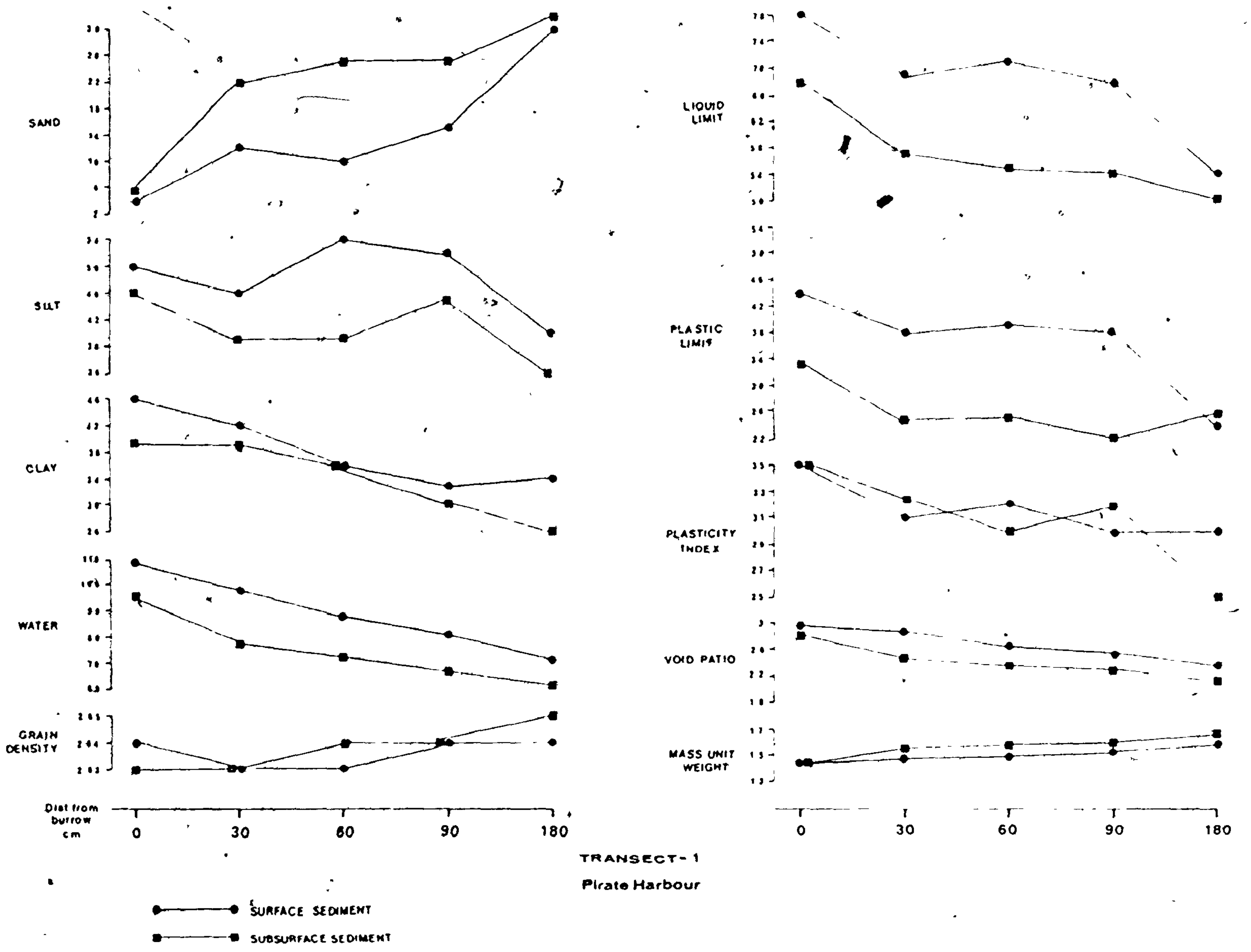
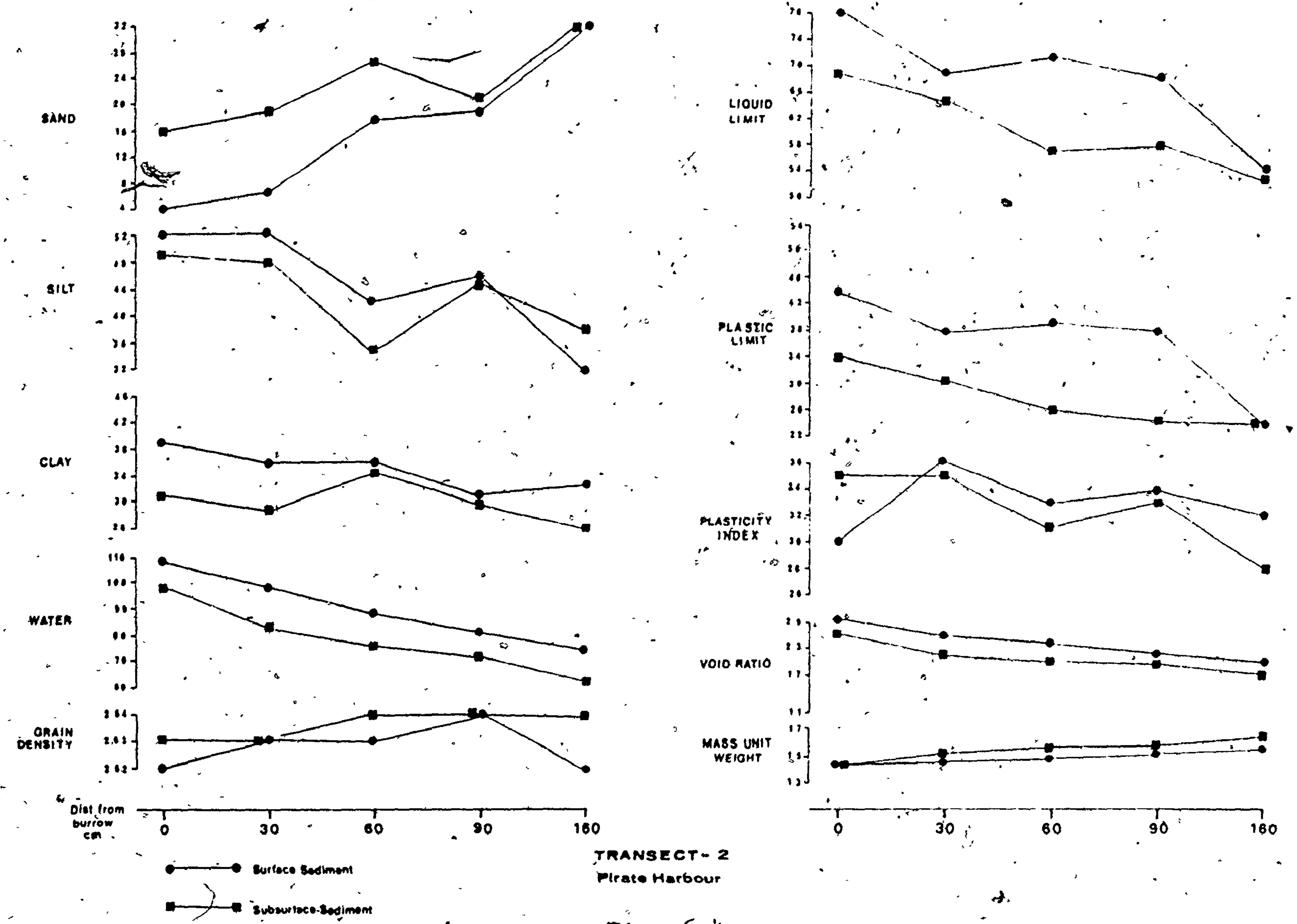
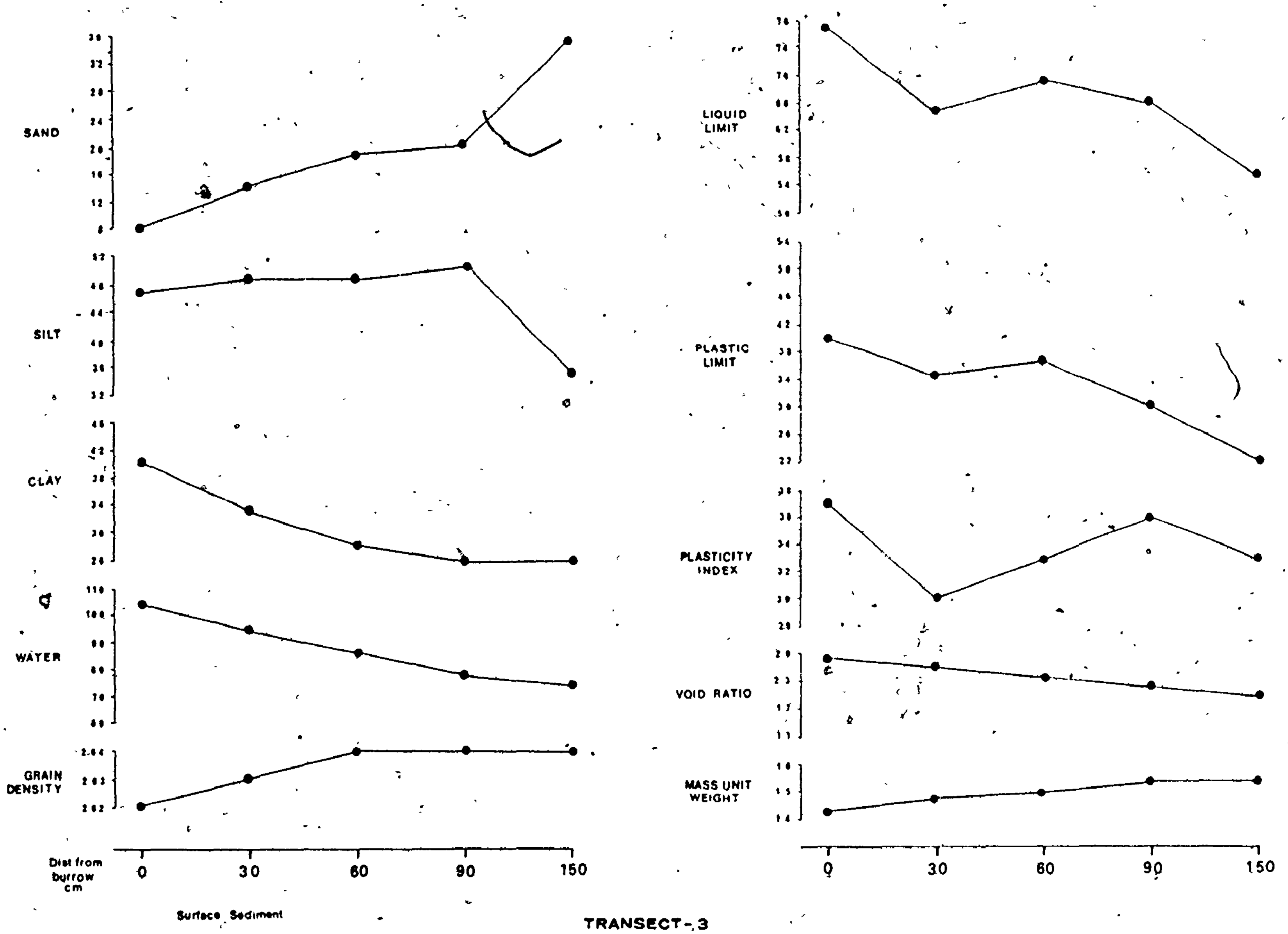

SAND
30
26
22
18
14
10
6
2
SILT
54
50
46
42
38
34
CLAY
46
42
38
34
30
26
WATER
110
100
90
80
70
60
GRAIN DENSITY
2.65
2.64
2.63
Dist from burrow cm
0
30
60
90
180
LIQUID LIMIT
78
74
70
66
62
58
54
50
PLASTIC LIMIT
54
50
46
42
38
34
30
26
22
PLASTICITY INDEX
35
33
31
29
27
25
VOID RATIO
3
2.6
2.2
1.8
MASS UNIT WEIGHT
1.7
1.5
1.3
0
30
60
90
180
TRANSECT-1
Pirate Harbour
SURFACE SEDIMENT
SUBSURFACE SEDIMENT

Fig. 6-3



TRANSECT- 2
Pirate Harbour

Fig. 6-4



TRANSECT-3
Pirate Harbour

Fig. 6-5

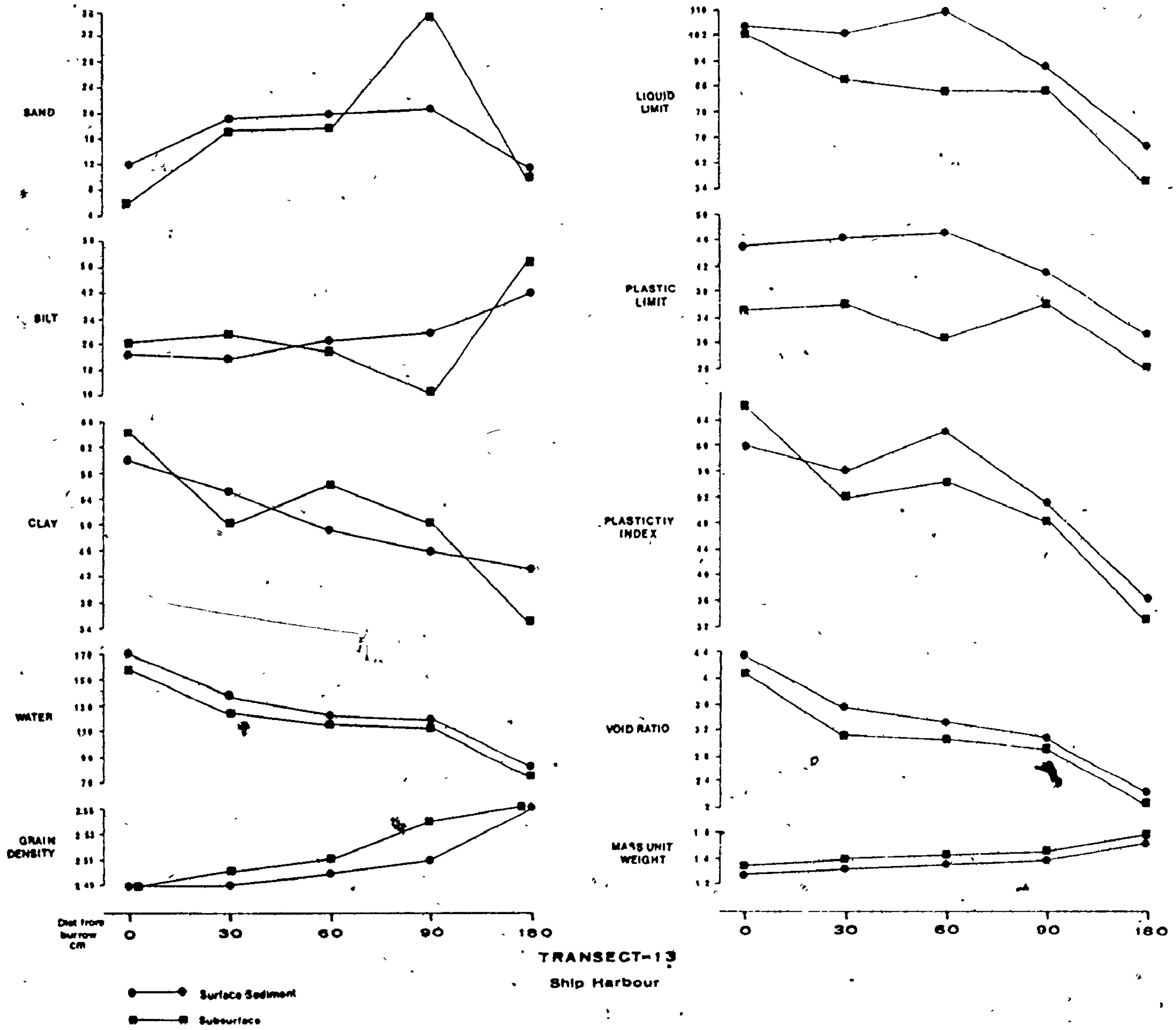
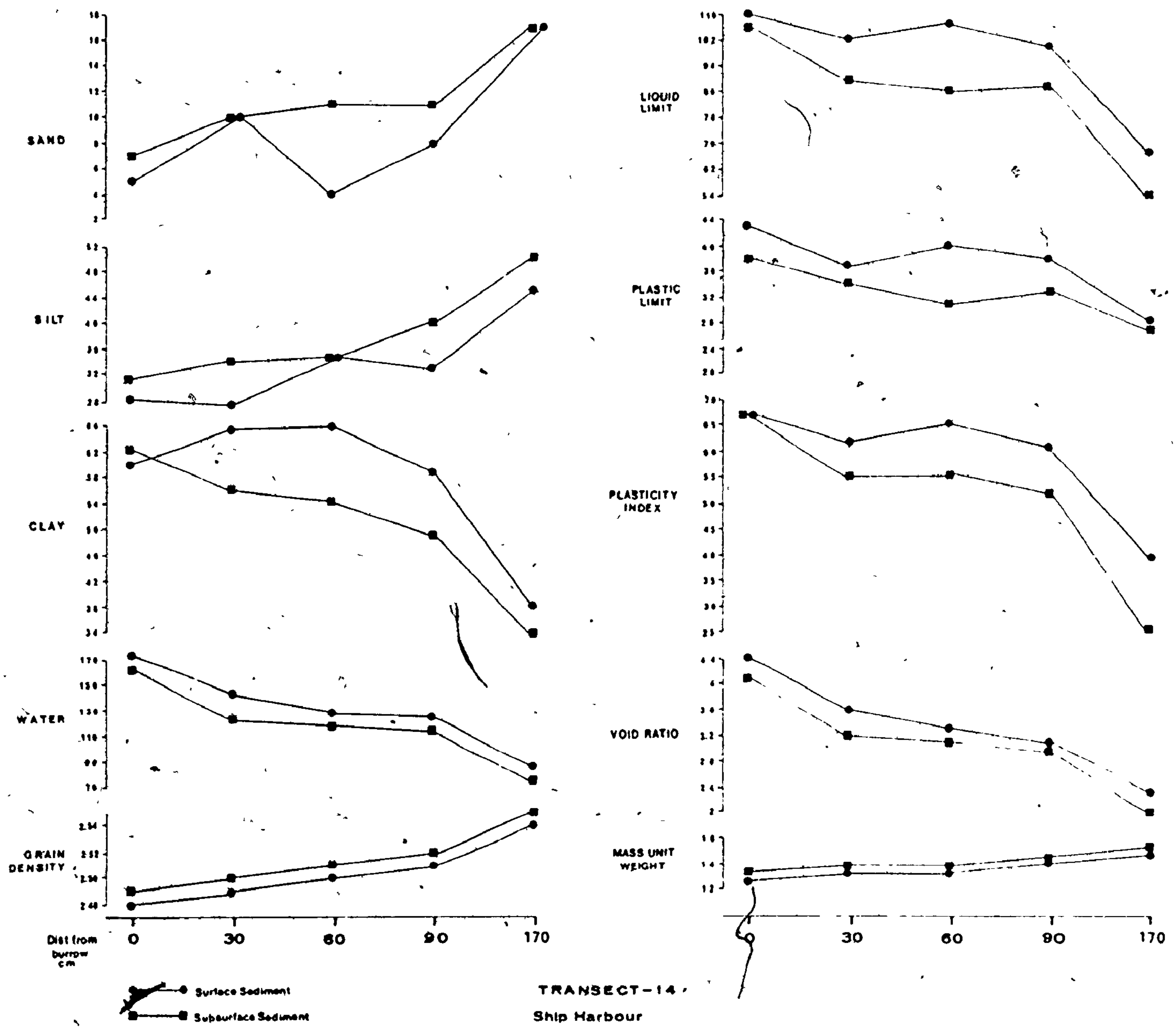
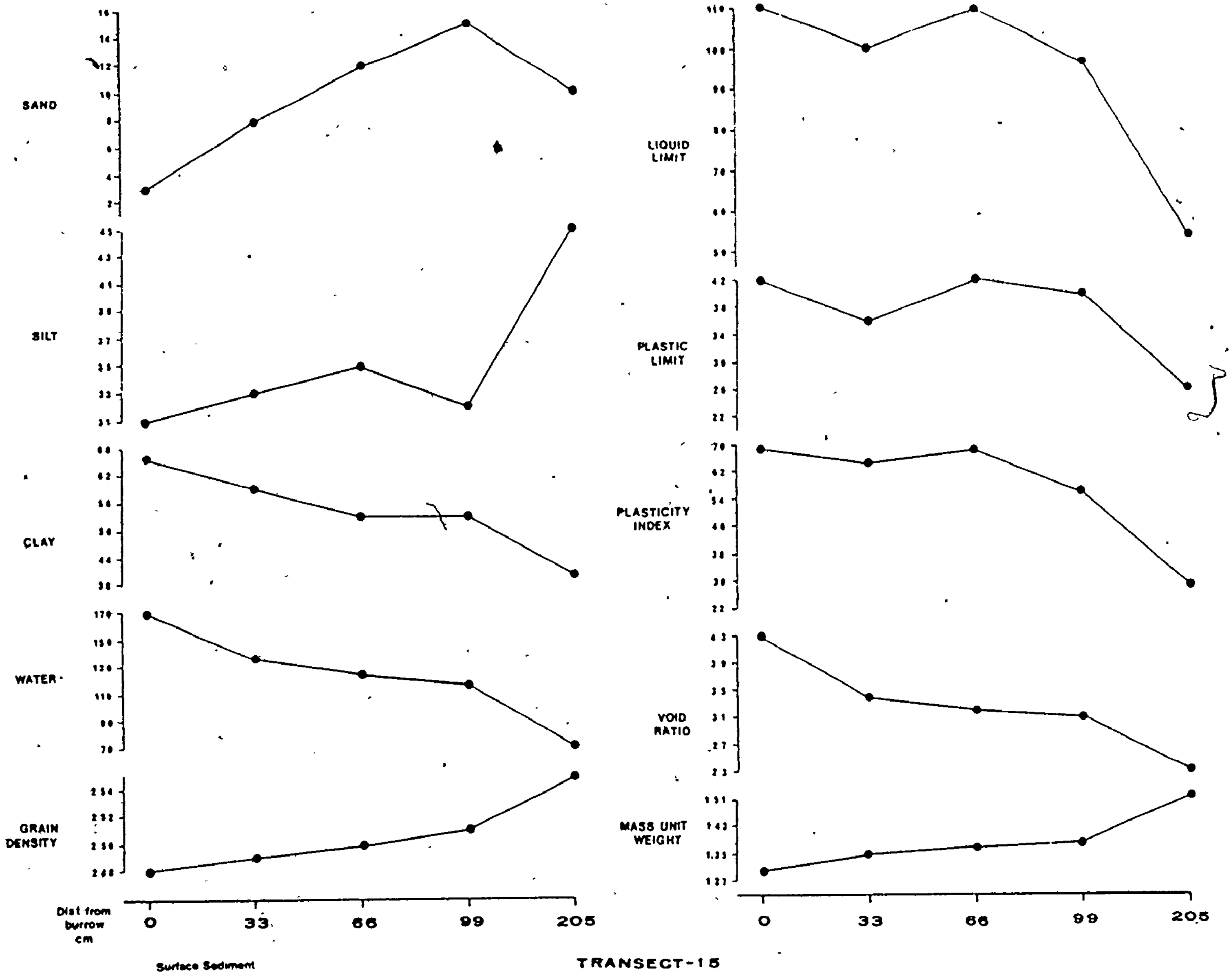

SAND
SILT
CLAY
WATER
GRAIN DENSITY
LIQUID LIMIT
PLASTIC LIMIT
PLASTICTIY INDEX
VOID RATIO
MASS UNIT WEIGHT
Dist from burrow cm
0
30
60
90
180
TRANSECT-13
Ship Harbour
Surface Sediment
Subsurface

Fig. 6-6



TRANSECT-14,
Ship Harbour

Fig. 6-7



TRANSECT-15

Ship Harbour

Fig. 6-8

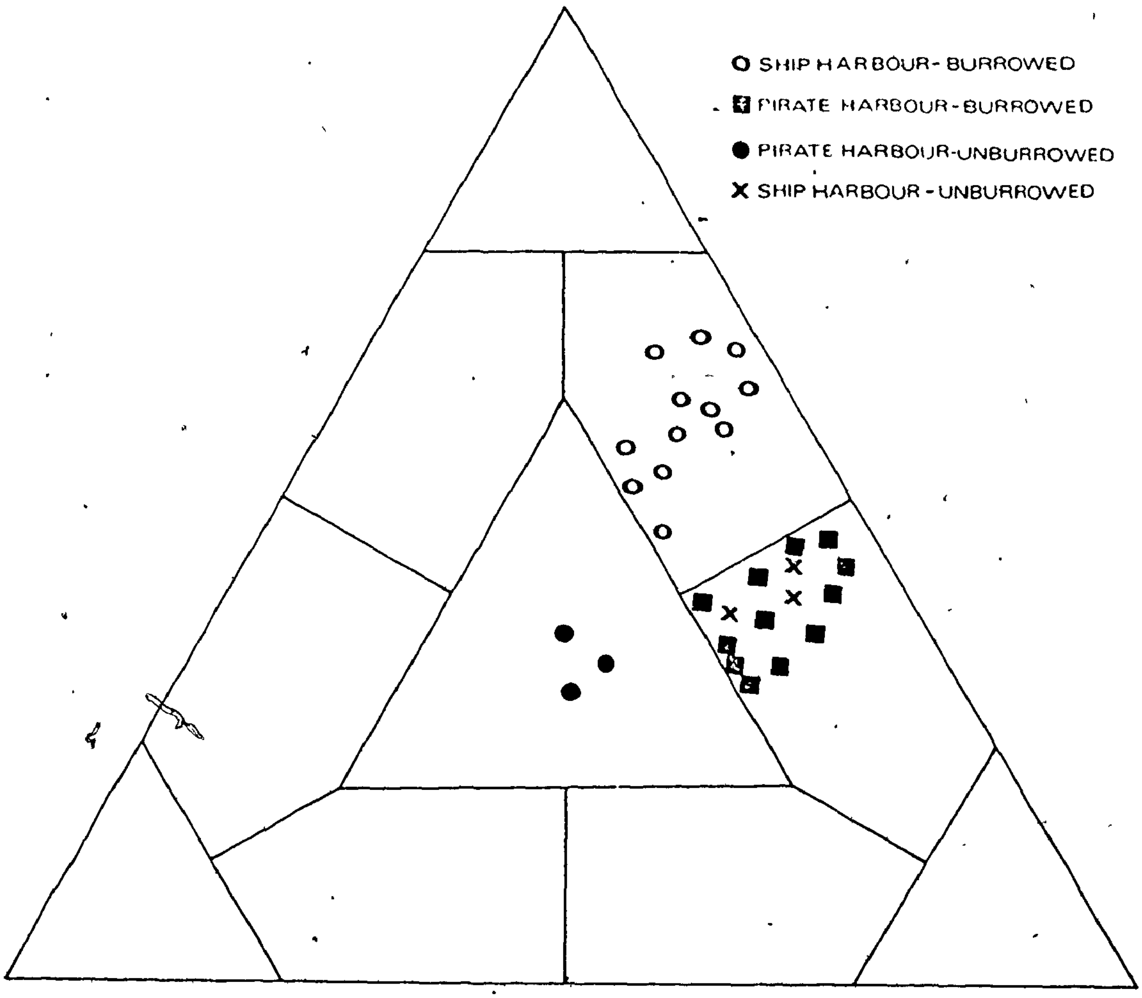
while the 25 samples from Pirate Harbour had a mean clay content of 36% (range: 26-46%). Pirate Harbour sediments contain more sand (mean sand content of 20%) than Ship Harbour (mean sand content of 12%).

There exist distinct differences, in both areas between burrowed and unburrowed sediments (Figure 6-9, 6-10). In Ship Harbour, sediments (both surface and subsurface) grade from silty clay to clayey silt. Clay content decreases and silt and sand content increase away from burrow openings. The same general relationship holds true in Pirate Harbour, where both surface and subsurface sediments grade from clayey silt to sand-silt-clay (Figure 6-9, 6-10) going horizontally away from the burrow opening (Figure 6-3, 6-4, 6-5).

b. Water content

In the Strait of Canso, water content values were significantly higher in the finer-grained sediments of Ship Harbour than in the coarser sediments of Pirate Harbour (Figure 6-11, 6-12). Values in Ship Harbour ranged from 76 to 170% dry weight, with a mean value of 123%. Pirate Harbour exhibited a range from 61 to 109% dry weight, with a mean value of 84%.

In both areas water contents decreased with increasing horizontal distance from the burrow opening. All transects displayed the greatest decline between the first



SURFACE SEDIMENTS

Fig. 6-9: Classification of surface sediments from Ship Harbour and Pirate Harbour.

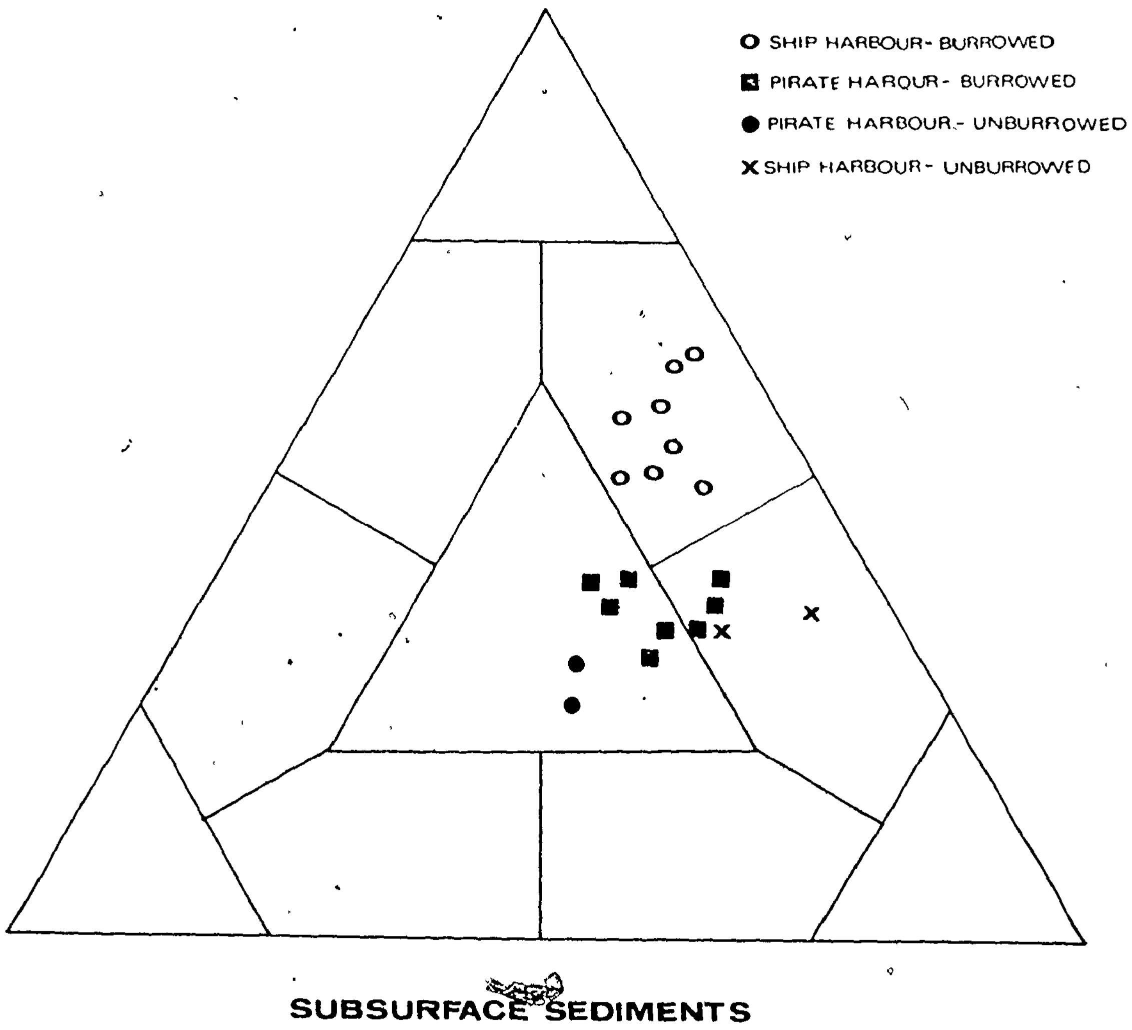


Fig. 6-10: Classificationof subsurface sediments from Ship Harbour and Pirate Harbour.

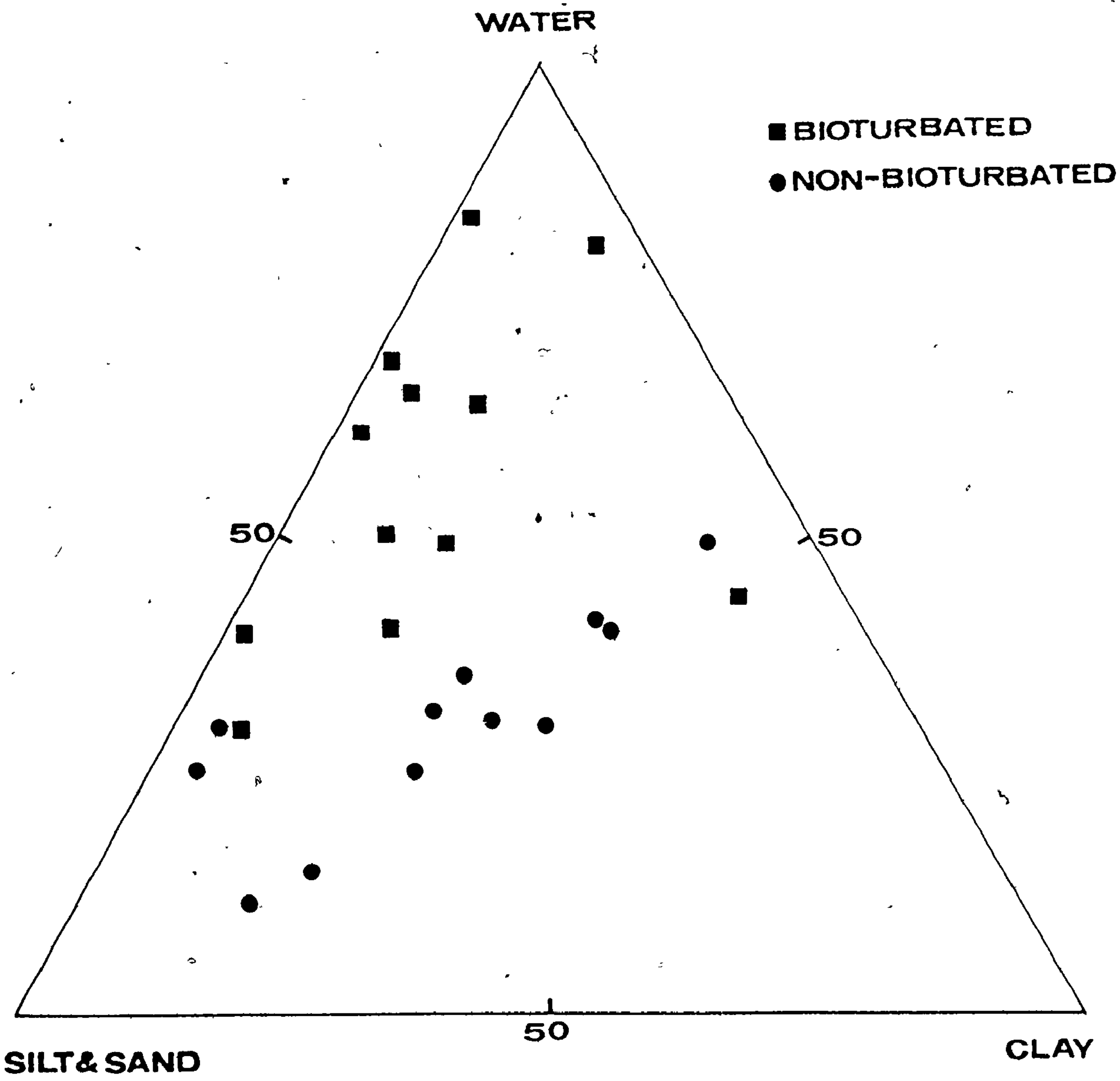


Fig. 6-II: Grain-size and water content classification of surface sediments from Canso Strait.

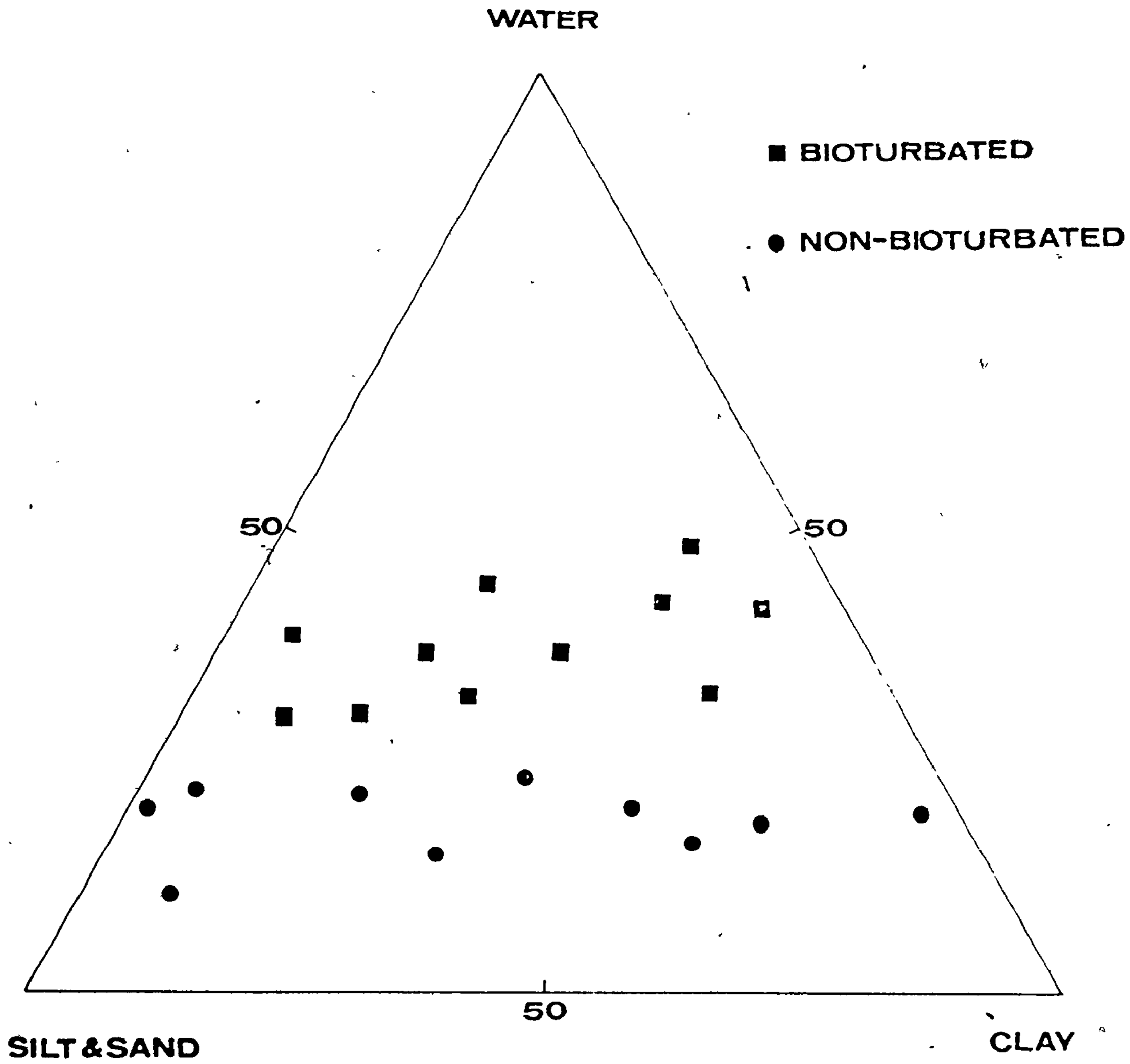


Fig. 6-I2: Grain-size and water content classification of subsurface sediment from Canso Strait (depth IO cm.).

two samples, closest to the burrow opening (Figure 6-6, 6-7, 6-8).

c. Grain density

The average grain density of a sediment is dependent on the densities of all the solid constituents (Hamilton and Menard, 1956). Since a typical marine substrate is composed of a multitude of different materials, each with their own density, the mean density of that sediment reflects the percentages of each of these materials. Quartz, which is the predominant constituent of marine sand, has a density of 2.65; clay, on the other hand, the dominant constituent of marine mud, displays an average density of 2.48 (Baas Becking and Moore, 1959). Organic matter is known to lower the average grain density of marine sediments (Baas Becking and Moore, 1959; Rashid and Brown, 1975). The distribution of average grain densities in the study area closely reflects the sedimentological differences between the two sub-areas. Pirate Harbour, which displays much higher sand contents, has an average grain density of 2.63. This is similar to results obtained on surface sediments from Australia (Baas Becking and Moore, 1959). Ship Harbour has an average grain density of 2.51, reflecting the increased mud and organic matter found in the surface sediments.

d. Atterberg limits and indices

Atterberg limits and indices are recorded in Tables 6-3 and 6-4. Generally, Ship Harbour displays much higher values than Pirate Harbour, which again reflects the differences in per cent mud and water content. Plasticity charts, which relate plasticity to liquid limit (Casagrande, 1948) were constructed for each sub-area (Figure 6-13, 6-14). The "A-line" on these charts represents an important empirical boundary. Plastic sediment containing organic colloids and typical organic silts and silty clays falls below the A-line, while typically inorganic clayey and silty sediment falls above it. In both charts there exist distinct differences between sediments termed burrowed and unburrowed. Surface sediments in burrowed areas are classified as organic silts and clays of high plasticity, while unburrowed areas fall into the inorganic, medium plasticity zone.

In addition to the plasticity index, the liquidity index was also examined in both sub-areas. In all cases, the values indicate that the sediment has a liquid nature. Generally, the highest values were obtained closest to the burrow. This decrease in value with increasing distance away from the burrow is more distinct in Pirate Harbour (Figure 6-3, 6-4, 6-5).

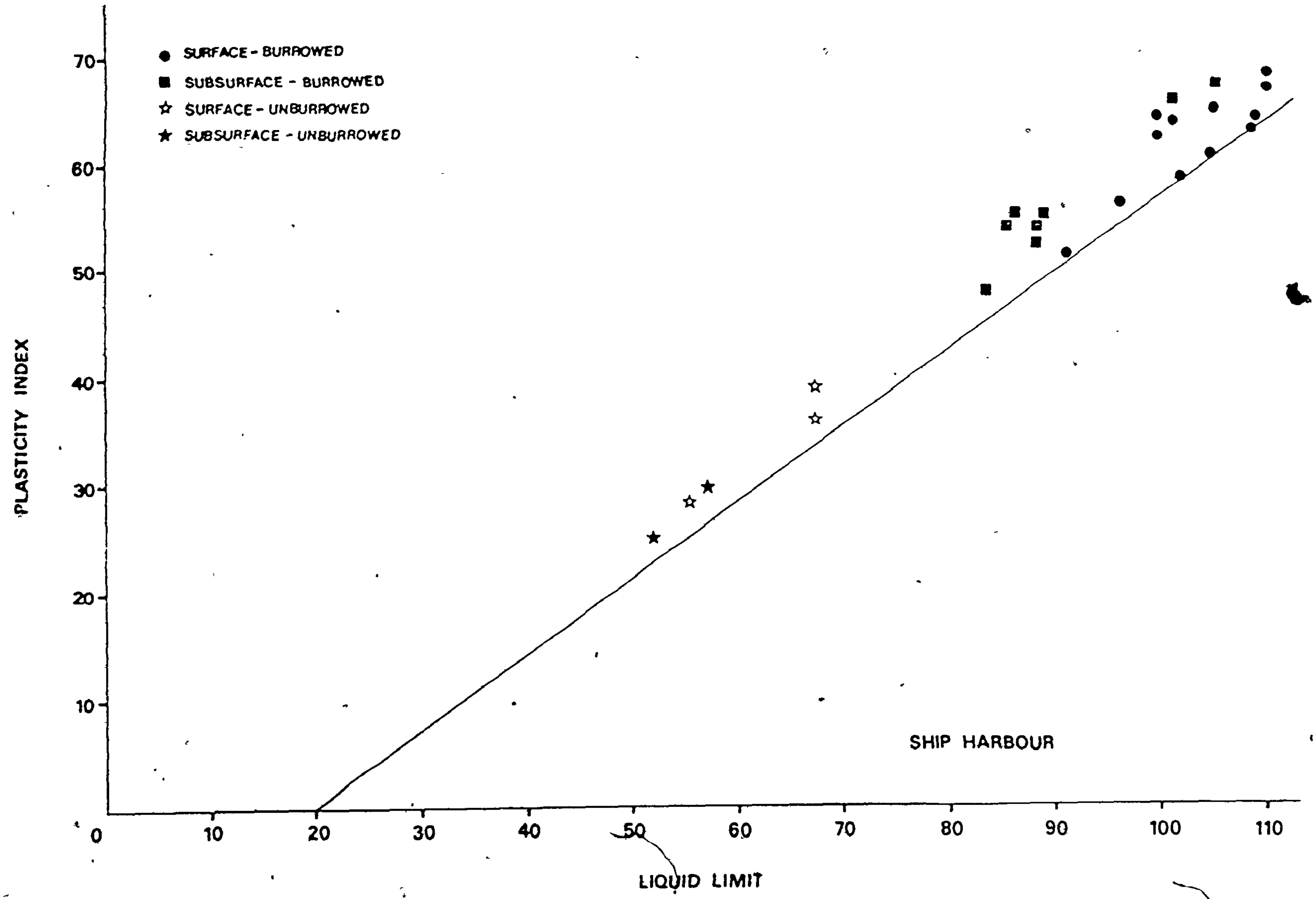


Fig. 6-13: Plasticity chart for samples from Ship Harbour.

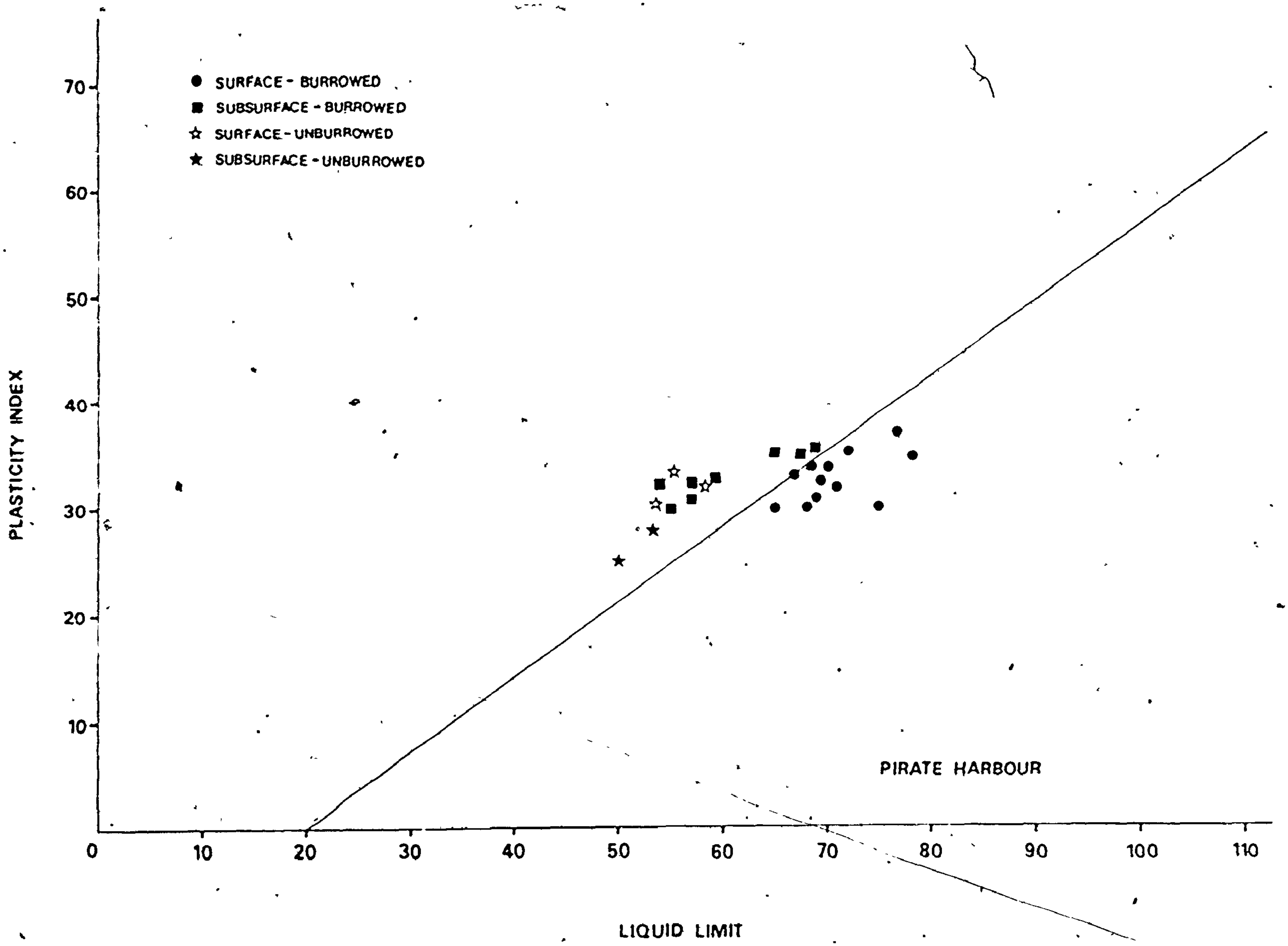


Fig. 6-14: Plasticity chart for samples from Pirate Harbour.

e. Activity

Activity charts were drawn for both sub-areas (Figure 6-15, 6-16). In Pirate Harbour (Figure 6-15) there exists little variation between burrowed and unburrowed sediments, although activity is slightly higher in the burrowed samples. All samples fall within the range 0.75 to 1.25, which is usually accepted as being normal (Skempton, 1953). Ship Harbour, on the other hand, displays great variations. Burrowed sediments range from normal to active (greater than 1.25), while unburrowed sediments range from normal to inactive (less than 0.75).

f. Void ratio, porosity and mass unit weight

Void ratio, porosity, and mass unit weight all reflect changes in water content and grain density and vary with these two properties (Tables 6-3, 6-4).

g. Overall trends

The transects were useful in establishing the overall effect of Axius burrows in the sub-areas. Table 6-5 summarizes the overall trends of the mass physical properties investigated. Generally, as the distance from the main burrow opening increases, per cent sand, per cent silt, grain density and mass unit weight increase; per cent clay, water content, liquid limit, plastic limit, plasticity index, and void ratio decrease.

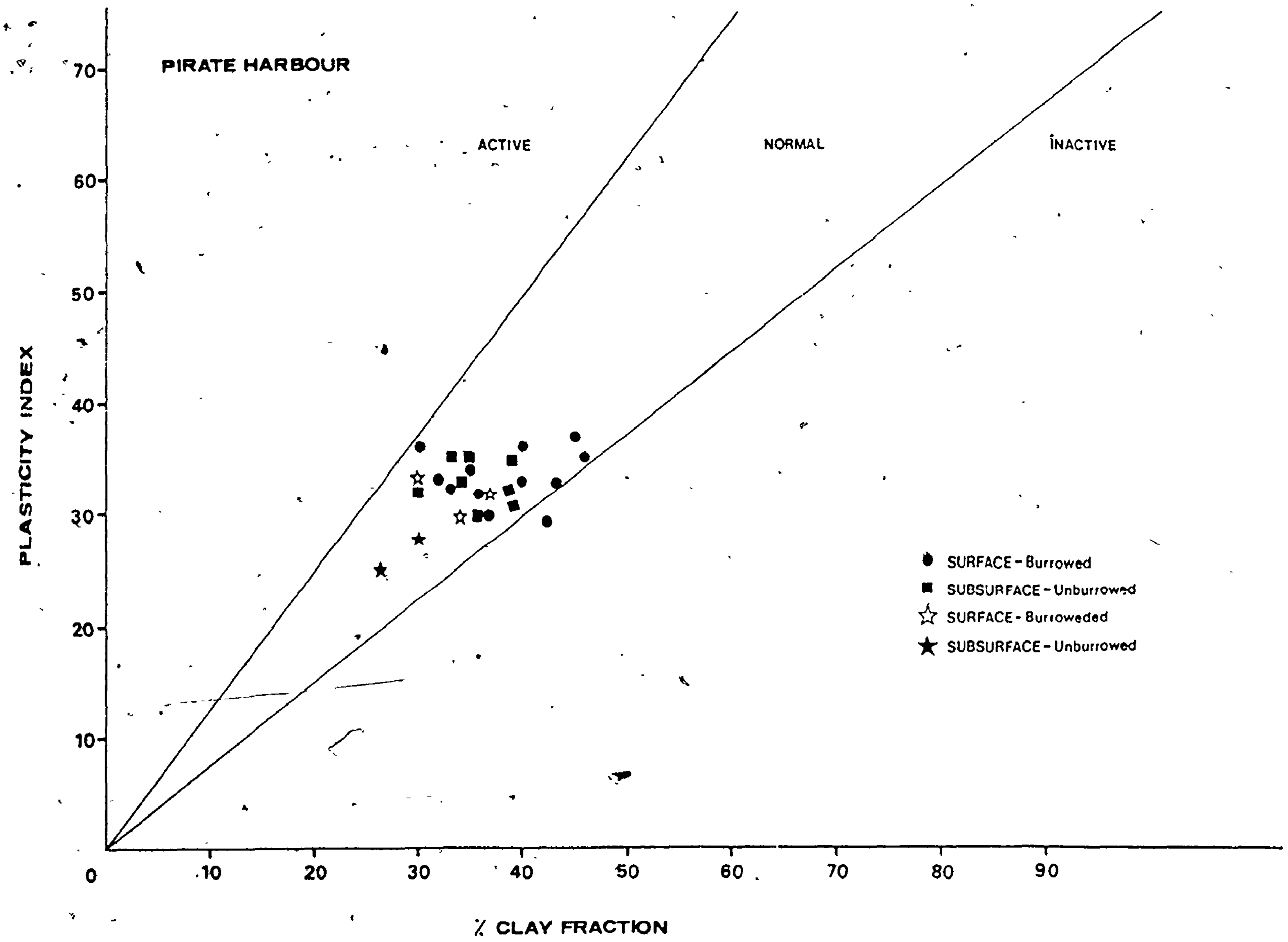


Fig. 6-15: Activity chart for samples from Ship Harbour.

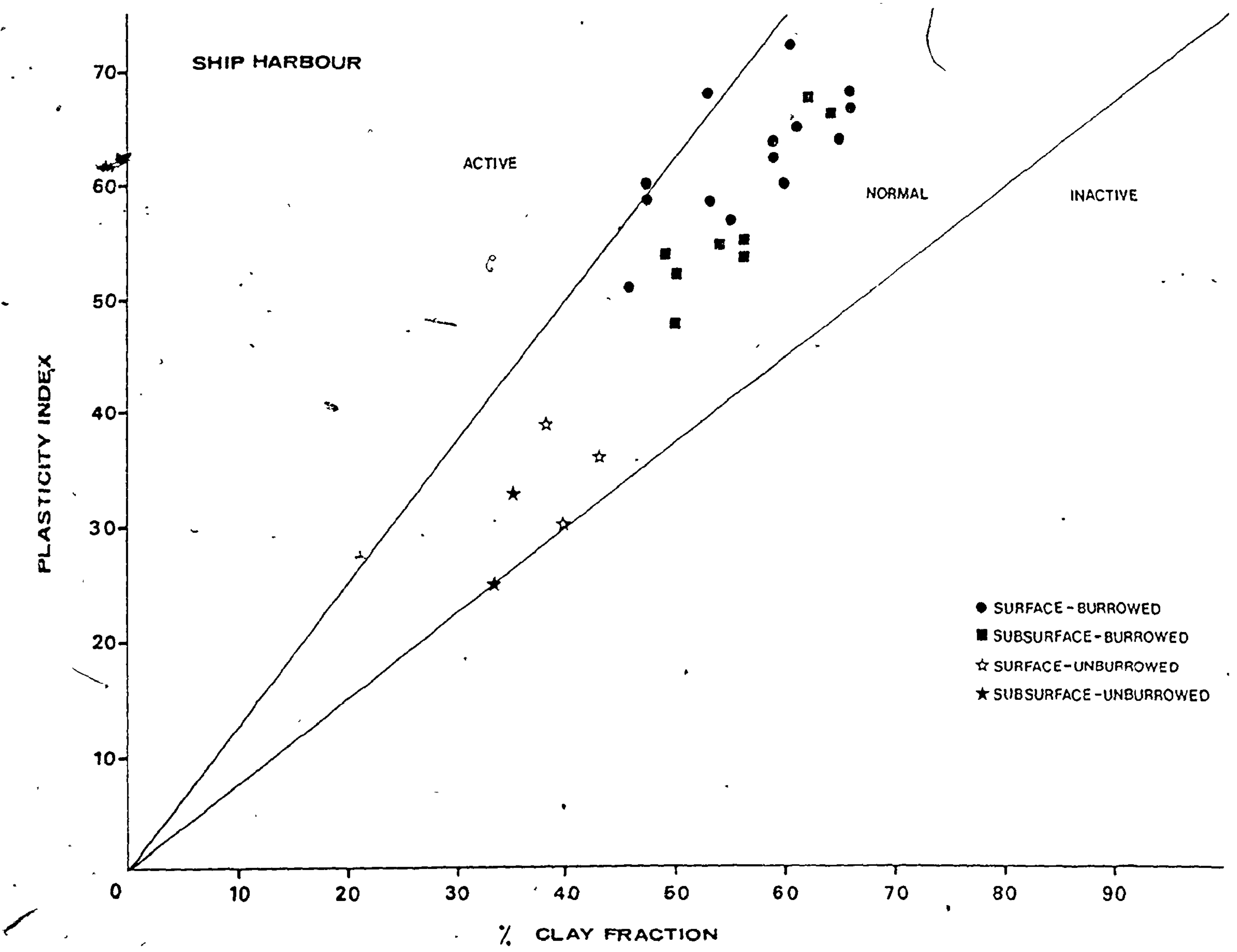


Fig. 6-16: Activity chart from samples from Ship Harbour.

Table 6-5: Summary of overall trends of the mass physical properties with increasing distance from the burrow opending.

Property	Ship Harbour		Pirate Harbour	
	Surface	Subsurface	Surface	Subsurface
Percent sand	increases	increases	increases	increases
Percent silt	increases	increases	decreases	decreases
Percent clay	decreases	decreases	decreases	decreases
Percent water	decreases	decreases	decreases	decreases
Grain density	increases	increases	no trend	no trend
L.L.	decreases	decreases	decreases	decreases
P.L.	decreases	decreases	decreases	decreases
P.I.	decreases	decreases	decreases	decreases
Void Ratio	decreases	decreases	decreases	decreases
Mass Weight	increases	increases	increases	increases

E. Inter-relationships of Mass Physical Properties

1. R-Mode Factor Analysis

A great deal of work has been done on the inter-relationships of the mass physical properties of marine sediments. Studies by Richards (1962), Holmes and Goodell (1964), Richards (1964), and Inderbitzen (1970), among others, have illustrated the extent to which these properties are interdependent. To better understand these relationships, an R-mode factor analysis was performed on the mass properties, of the surface sediments of both Pirate Harbour and Ship Harbour. This method is a multivariate technique for the grouping of variables into principal associations based on their mutual linear correlation coefficients (Krumbein and Graybill, 1965). The factor analysis was carried out using a standard program modified by Dalrymple (personal communication, 1976), in which no scaling factor or transformations were used. The program employed orthogonal rotation by the varimax method (Kaiser, 1953), rotating all eigenvectors for which the eigen-factors were greater than one. The factor solutions provide information on:

(i) loading - the strength of a particular element in a factor;

(ii) communality - the amount of the total variability of each element explained in a given factor model (a low value suggests either analytical error or the presence of other specific sources of variation (Shaw, 1974);

(iii) eigenvalues (expressed in per cent) - the amount of the total data variability explained by each model; and

(iv) factor scores - the strength of each factor in each sample area.

Limitations on this procedure are imposed mainly by the subjective interpretation of the associations derived from the factor analysis (Reison, 1975). It should also be emphasized that a series of solutions may result from this type of analysis and that the selection of the most appropriate model is based on the recognition of associations considered meaningful in terms of geological processes. The complicated theory of factor analysis will not be reviewed here, but detailed accounts may be found in Cattell (1965a,b) and Harmon (1967).

The variables used in the present factor analysis include: per cent sand, per cent silt, per cent clay, per cent water, liquid limit, plastic limit, plasticity index, grain density, distance from burrow, porosity, void ratio, and mass unit weight.

2. Results

a. Pirate Harbour

In the surface sediments of Pirate Harbour, the correlation matrix (Table 6-6) showed strong mutual correlations among virtually all of the variables studied. The rotated factor matrix of the mass physical data from the 15 mud samples is given in Table 6-7. Two factors account for 86% of the total variance in the original data. The rotation of two factors provided the best model for explaining most of the variance. The factors and the relative magnitudes of their loading are depicted diagrammatically in Figure 6-17.

(i) Factor one

Factor one is statistically dominant and accounts for over 76% of the total variance among the variables (Table 6-7). It is characterized by a very strong association of per cent clay, per cent water, liquid limit, plastic limit, porosity, and void ratio (Figure 6-17). The inverse relationship of this association with per cent silt, grain density, distance from burrow, and mass unit weight is indicated by the high positive loadings on these four variables (Figure 6-17). This factor indicates that, as the distance from the burrow increases, the per cent silt, grain density, and mass unit weight increase, while per cent clay, per cent water, liquid limit, plastic limit, porosity, and void ratio decrease.

Table 6-6: Correlation coefficients of mass properties from surface sediments of Pirate Harbour

% sand	1.000											
% silt	-.858	1.000										
% clay	-.708	.244	1.000									
% water	-.904	.617	.858	1.000								
L. L.	-.937	.798	.671	.857	1.000							
P. L.	-.948	.816	.667	.863	.946	1.000						
P. I.	-.200	.145	.178	.197	.400	.081	1.000					
Grain Density	.627	-.384	-.655	-.733	-.535	-.570	-.032	1.000				
Dist. from burrow	.938	-.763	-.720	-.949	-.919	-.905	-.268	.679	1.000			
Porosity	-.911	.636	.844	.997	.867	.870	.207	-.724	-.965	1.000		
Void Ratio	-.897	.605	.861	.998	.854	.858	.201	-.714	-.946	.997	1.000	
Mass Weight	.915	-.652	-.831	-.996	-.874	-.880	-.200	.747	.968	-.997	-.992	1.000

Table 6-7: Rotated factor matrix for 15 surface samples from Pirate Harbour

Variable	Factors 1	2	Communality
Percent sand	.82	.52	.944
Percent silt	-.48	-.7	.726
Percent clay	-.88	-.02	.775
Percent water	-.94	-.29	.975
L. L.	-.72	-.67	.959
P. L.	-.8	-.47	.872
P. I.	.07	-.71	.503
Grain Density	.83	-.06	.692
Dist. from burrow	.85	.48	.962
Porosity	-.94	-.32	.977
Void Ratio	-.94	-.29	.966
Mass Weight	.94	.32	.983
Eigenvalve	9.236	1.099	
Variance explained by factor (%)	76.97	9.16	
Variance cummulative (%)	76.97	86.13	

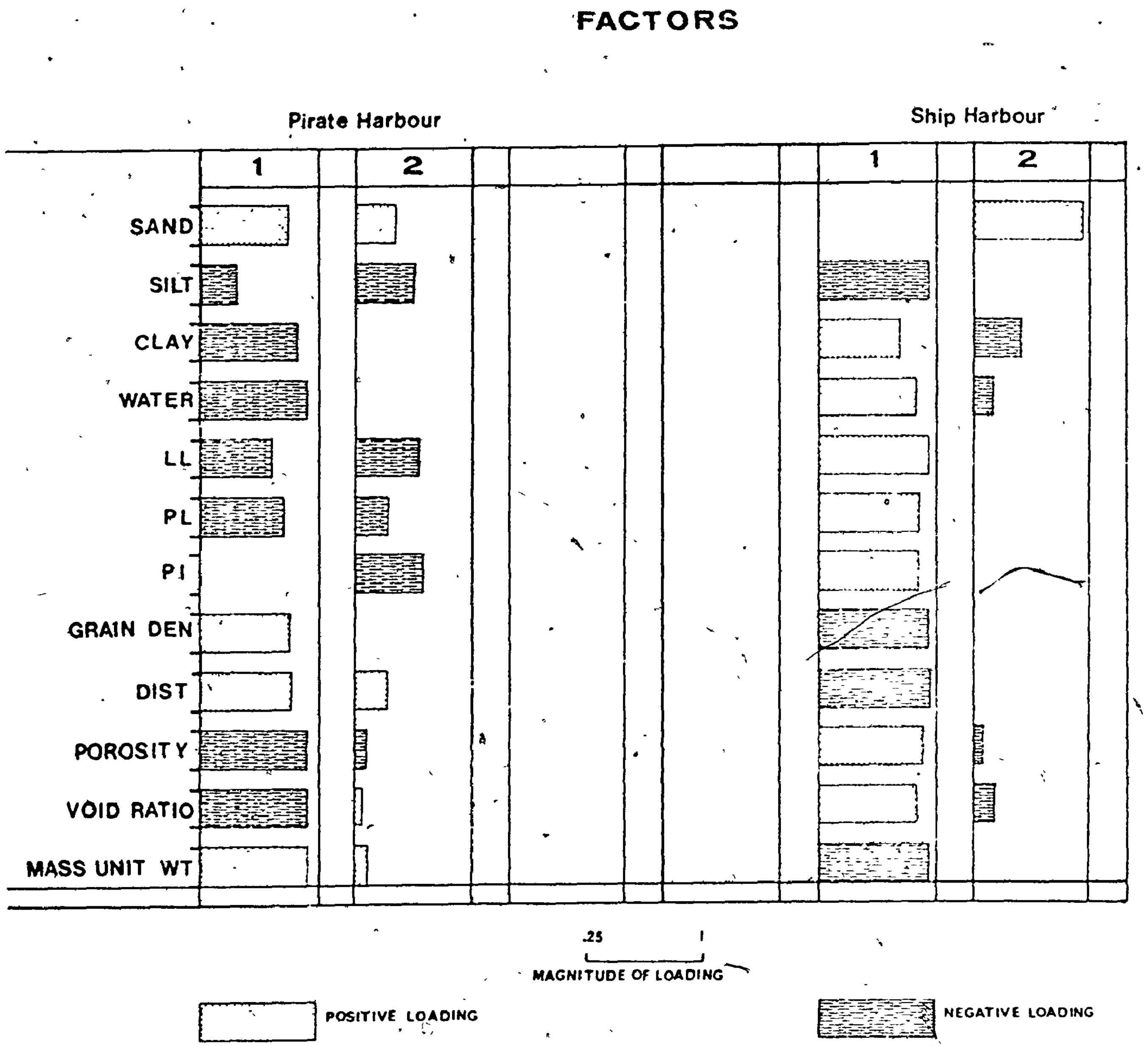


Fig. 6-17: Diagrammatic representation of results of factor analysis (only factor loadings greater than 0.25 are illustrated).

These observations agree with previous work. Richards et al. (1974) conducted a study on the effect of water content on void ratio and mass unit weight. He illustrated that as the water content increases, the void ratio also increases, while the mass unit weight decreases. Since it is known that void ratio is intimately linked to porosity (Lambe, 1951), any increase in void ratio will be translated into a similar increase in porosity. Inderbitzen (1970), among others, has shown that in normal marine sediments water content is linked directly to the per cent clay sized fraction. As this per cent increases, there is a corresponding increase in the water content.

The plastic and liquid limits of a sediment may be defined in terms of natural water content and the amount of clay present (Yong and Warkentin, 1975). The liquid limit has been shown to vary directly with variations in water content by Einsele (1967) in sediments from the Red Sea. The plastic limit varies much less than the liquid limit, and has been shown to be dependent on both the type and amount of clay present (Yong and Warkentin, 1975). Rashid and Brown (1975) have illustrated that increases in the organic matter present in marine sediments will significantly increase both the liquid and plastic limits.

Since the average grain density of any sample is dependent on the densities of all the solid constituents present in the sample (Hamilton and Menard, 1956), any change in this value must be the result of changes in the constituents of the sample. This factor indicates that the average grain density increases with increasing distance from the burrow opening. Baas Becking and Moore (1959) point out that a decrease in average grain density is primarily a function of increasing organic content. This has recently been substantiated by Rashid and Brown (1975).

From these complex interactions the factor can thus be interpreted in terms of clay content, water content and distance from the burrow. The combination of decreasing clay content and water content with increasing distance from the burrow explains the association of variables in this factor. The lone exception is the variation in grain density, which can be explained in terms of organic matter. The direct relationship between increasing grain density with increasing distance from the burrow, suggests that organic matter decreases in concentration away from the burrow.

(ii) Factor two

This factor is characterized by strong loadings on per cent silt, liquid limit, and plasticity index and a lesser, but still significant loading, on plastic limit (Figure 6-17). Factor two accounts for over 9% of the total variance among the variables (Table 6-7). It is interpreted as reflecting the plasticity variation in the sediment. An inverse relationship to the above association is indicated by the positive loadings on per cent sand and distance from the burrow (Figure 6-17).

The plasticity of a sample can be defined as its ability to change shape continuously under applied stress and to retain this new shape on removal of the stress (Jumikis, 1962). The plasticity index reflects both the liquid limit and the plastic limit (PI = LL - PL). Thus, any changes in either the plastic limit or the liquid limit will be reflected in changes in the plasticity index. Soil scientists have stressed that plasticity varies with the amount and type of clay in a given sample (Terzaghi, 1943; Lambe, 1951; Yong and Warkentin, 1975). In addition to clays, silts also exhibit a degree of plastic behaviour (Terzaghi, 1943). This factor association indicates that variations in plasticity may be related to changes in the sand-silt ratio. It has long been known that the liquid limit of a sediment will decrease as the clay content decreases, but that the liquid limit per unit weight of clay will remain virtually constant. Thus, the factor can be explained in terms of plasticity, textural variation and the distance from the burrow opening. As the lateral distance from the burrow opening increases, the sand-silt ratio increases and plasticity decreases.

b. Ship Harbour

In the surface sediments of Ship Harbour, the correlation matrix (Table 6-8) again shows strong mutual correlations among virtually all of the variables studied. The rotated factor matrix of the mass physical data from 15 mud samples is depicted in Table 6-9. Two factors account for over 94% of the total variance in the original data. The factors and the relative magnitude of their loadings are depicted diagrammatically in Figure 6-17.

(i) Factor one

Factor one is statistically dominant and accounts for over 83% of the total variance among the variables (Table 6-9). It is the same as factor one in Pirate Harbour.

(ii) Factor two

Factor two is characterized by a strong positive loading on per cent sand. An inverse association with per cent clay is indicated by its negative loading (Figure 6-17). This factor accounts for over 10% of the total variance found among the variables (Table 6-9). Unlike factor two in Pirate Harbour, there exists no association with the plasticity of the sample. This factor merely indicates changes in the clay-sand ratio; as the per cent sand in the sample increases, there is a corresponding decrease in the per cent clay.

Table 6-8: Correlation coefficients of mass properties from surface sediments of Ship Harbour

% sand	1.000											
% silt	.050	1.000										
% clay	-.622	-.807	1.000									
% water	-.407	-.828	.870	1.000								
L. L.	-.204	-.929	.854	.835	1.000							
P. L.	.081	-.844	.623	.744	.895	1.000						
P. I.	-.331	-.989	.904	.815	.974	.772	1.000					
Grain Density	.267	.936	-.885	-.933	-.938	-.815	-.926	1.000				
Dist. from burrow	.289	.919	-.881	-.959	-.926	-.822	-.906	.989	1.000			
Porosity	-.331	-.899	.889	.984	.903	.806	.881	-.973	-.985	1.000		
Void Ratio	-.408	-.823	.867	1.000	.830	.741	.810	-.930	-.956	.983	1.000	
Mass Weight	.304	.917	-.887	-.974	-.917	-.817	-.896	.983	.989	-.998	-.972	1.00

Table 6-9: Rotated factor matrix for 15 surface samples from Ship Harbour

Variable	Factors 1	2	Communality
Percent sand	-.06	.99	.976
Percent silt	-.97	.00	.935
Percent clay	.79	-.57	.951
Percent water	.89	-.38	.929
L. L.	.96	-.12	.932
P. L.	.92	.18	.886
P. I.	.90	-.26	.878
Grain Density	-.96	.25	.979
Dist. from burrow	-.96	.25	.979
Porosity	.94	-.30	.976
Void Ratio	-.88	-.38	.925
Mass Weight	-.96	.27	.983
Eigenvalve	10.035	1.290	
Variance explained by factor (%)	83.63	10.75	
Variance cummulative (%)	83.63	94.38	

3. Discussion

Factor analysis on samples in the Strait of Canso has established associations between certain mass physical properties. These associations conform to known relationships established by previous investigators. Analysis indicates that an inverse relationship between water content and per cent clay in conjunction with distance from the burrow opening may explain most of the variable associations present.

The distribution of factor scores in both Pirate Harbour (Table 6-10) and Ship Harbour (Table 6-11) illustrates the importance of the burrow opening, in the establishment of the various factors. In all cases there is a decrease of factor score with increasing distance from the burrow opening.

F. Variability of Mass Physical Properties in the Strait of Canso

The degree of lateral variation for each property is expressed by the coefficient of variation $V = R/\bar{x} \times 100$ (Balsley, 1964). The coefficient of variation or relative dispersion represents a measure of the range R (difference between maximum and minimum values) expressed as a per cent of the mean $\bar{x}$. A low value for the coefficient of variation simply indicates that the particular property was not

Table 6-10: Varimax factor scores for surface sediments from Pirate Harbou

Sample Number	Factors 1	2	Dist. from burrow (cm.)
1-1	-34.593	-169.966	0
1-2	-28.148	-136.775	30
1-3	-24.575	-128.981	60
1-4	-19.676	-105.916	90
1-5	- 5.664	-30.974	180
2-1	-34.681	-168.279	0
2-2	-28.925	-148.116	30
2-3	-23.089	-114.951	60
2-4	-19.287	-103.501	90
2-5	- 8.050	-40.240	160
3-1	-33.258	-164.503	0
3-2	-26.732	-132.332	30
3-3	-22.381	-118.680	60
3-4	-17.435	-100.018	90
3-5	- 7.952	-44.077	150

Table 6-11: Varimax factor scores for surface sediments from Ship Harbour

Sample Number	Factors 1	2	Dist. from burrow (cm)
13-1	43.991	-103.647	0
13-2	37.222	-78.996	30
13-3	33.452	-67.155	60
13-4	26.066	-53.775	90
13-5	7.580	-26.826	180
14-1	45.877	-113.353	0
14-2	38.423	-92.529	30
14-3	34.059	-87.221	60
14-4	29.232	-72.647	90
14-5	8.835	-22.883	170
15-1	45.219	-113.797	0
15-2	36.196	-88.804	33
15-3	33.884	-76.020	66
15-4	27.789	-61.833	99
15-5	2.110	-17.142	205

appreciably influenced by varying environmental conditions, or that there was little variation in the environment, and the samples are closely related in regard to the particular property. In general, high values may indicate variability in the depositional environment. Values of V greater than the reproducibility errors for each property, represent natural variations among samples. This method closely parallels that described for deep-sea sediments by Bennett et al. (1968).

This coefficient of variation was applied to all the properties measured in the six transects previously discussed, in Ship Harbour (Table 6-12) and Pirate Harbour (Table 6-13). Earlier variability studies, all on deep-sea sediments, were concerned with the differences within a single core (Weber and Kleiman, 1960; Richards and Keller, 1962); with several cores over extensive areas of the sea (Richards, 1964; Keller and Bennett, 1970); or differences between major oceans (Keller and Bennett, 1968). Bennett et al. (1970) conducted variability studies on three closely spaced cores in the Whiting Basin, southwest of Vieques Island, Puerto Rico. They concluded that high variations in texture appeared to be the major factor contributing to the variations of several other properties.

1. Reproducibility Errors

Test procedures for the mass physical properties investigated have been outlined earlier. Silt and clay fractions were determined by pipette analysis (Folk, 1974) and per cent sand was obtained by wet sieving. Studies on terrigenous and glacial marine sediments (similar to the sediments of the Strait of Canso) by Bader (1957) show that the average reproducibility for a given size grade determination was ±0.2%, and that differences greater than ±0.4% probably represent actual sample variations. Reproducibility of ±2% to 5% of the measured values has been reported for the determination of the Atterberg limits (Olmstead and Johnston, 1955; Sowers, 1965). Variations greater than this are considered as representing natural variations in the properties rather than differences in analytical technique.

The determination of water content, mass unit weight, and grain specific gravity followed standard techniques. Values greater than ±1% of the observed values for water content and mass unit weight, and ±0.5% for grain specific gravity were considered to reflect natural variations among samples (Bennett <u>et al</u>., 1970). Void ratio and porosity are computed from water content, mass unit weight and grain specific gravity, and are subject to any error in these values. Bennett <u>et al</u>. (1970) showed that void ratio was probably in error by less than ±3% of the observed values.

It should be stressed that any loss of water through evaporation from the time of extracting the sample in the laboratory to its weighing is considered negligable. Because differences between samples, rather than absolute values, were of importance in this phase of the study, careful and consistent techniques were employed to ensure a uniform procedure.

2. Variability

Analysis of the coefficients of variation obtained for the mass physical properties of the sediments from Ship Harbour (Table 6-12) and Pirate Harbour (Table 6-13) reveals that in all cases the value of V is greater than the reproducibility errors and represent natural variations among samples.

Grain specific gravity and saturated mass unit weight reveal the smallest variations. Values for grain specific gravity exhibited higher variation in the surface sediments, which may reflect higher organic content. Mass unit weight, on the other hand, attains maximum variation in subsurface samples due to sediment packing with increasing depth.

Variation in water content attains a maximum value of 70% in Ship Harbour, and even the lowest V_δ value of 33% (in Pirate Harbour) is much greater than the estimated reproducibility error (±1%). It is of interest to note that, in both areas, maximum variation is exhibited in subsurface sediments, which implies that the activity of the shrimp in altering water content values is just as important in the subsurface as it is at the sediment-water interface. This is in contrast to earlier investigations which indicate that generally uniform water contents are present at any particular horizontal horizon within the sediment column (Weber and Kleiman, 1960). Variation within void ratio is responsive to changes in water content because in a unit volume, the water content (volumetric) is equivalent to void ratio. This is reflected in the similar coefficients of variation of void ratio and water content (Tables 6-12, 6-13).

Variations in texture are high and undoubtedly represent natural differences in the sand-silt-clay content (Tables 6-12, 6-13). Both areas exhibit the greatest variation in per cent sand, up to 197% in Pirate Harbour and 193% in Ship Harbour. This conforms to the earlier work of Bader (1957), who found that the greatest variations in texture occurred in the coarse fraction. Per cent silt exhibited variations of up to 118% in Ship Harbour and 49% in Pirate Harbour, while per cent clay displayed variations of up to 57% and 49% in Ship and Pirate Harbours, respectively. Indications are that major textural differences can be explained in terms of a shifting sand-silt-clay ratio with increasing distance from the burrow opening.

The liquid and plastic limits vary as much as 63% and 57%, respectively (Tables 6-12, 6-13). Maximum variation occurs in transects that display the greatest variation in texture and water content. The coefficient of variation for the liquid and plastic limits varies directly, in most cases, with the coefficient for per cent clay, and reflects the dependence of these limits on the clay content of the sample. This same relationship holds true for water content.

The high coefficients of variation in liquidity index and plasticity index are due to the variations in natural water content, plastic limit and liquid limit. Even small differences in these properties appreciably affect the Atterberg indices, as is readily seen by examination of the formulae:

$$PI = LL - PL \qquad \text{and} \qquad LI = \frac{W - PL}{LL - PL}$$

Variation in activity attains values of up to 55% and 39% in Ship and Pirate Harbours, respectively. High variations in activity are due to high variations in per cent clay and plasticity index, since

$$Ac = \frac{PI}{\%\ clay}$$

3. Discussion

Variability of certain physical properties was determined for six transects in selected areas of the Strait of Canso. Consistent laboratory techniques were used to ensure a minimum reproducibility error for the various tests in order to determine natural lateral differences between samples.

Variability was determined using the coefficient of variation, V. Analysis indicates that, in all cases, the coefficient of variation exceeded the reproducibility error for each property and reflected natural variation along the transect. Values of V ranged from less than 1% for grain specific gravity, to as high as 197% for per cent sand. The greatest variation among the largest number of properties occurred in Ship Harbour. Of the 12 properties studied, only plastic limit displayed a higher coefficient of variation in Pirate Harbour; all of the other properties exhibited the highest variation in Ship Harbour. This indicates that the sediments of Pirate Harbour are more uniform. Texture and water content were found to be the most important factors responsible for the variations in the mass physical properties and displayed the greatest degree of correlation with changes in the other properties. Their influence is shown to be more important in the subsurface samples of Ship Harbour than they are in Pirate Harbour.

The sediments investigated are from approximately the same environment and are influenced by similar hydrological regimes, yet considerable local variation exists amongst the mass physical properties. The nature of the transects indicate that the observed variation is a function of distance from a burrow opening. The influence of the burrowing thalassinid <u>Axius serratus</u> is greater in the finer sediments of Ship Harbour, which reflect greater horizontal variation in both surface and subsurface samples.

G. Summary and Discussion

The mass physical properties investigated in the Strait of Canso were determined using standard testing procedures. Three horizontal transects were sampled and tested in each sub-area. Transects were established in order to illustrate the effect of the proximity to the main burrow opening. As the distance from the burrow increased, per cent sand, per cent silt, grain density and mass unit weight increased and per cent clay, per cent water, liquid limit, plastic limit, plasticity index, and void ratio decreased.

R-mode factor analysis indicated that the inverse relationship between water content and per cent clay, in conjunction with distance from the burrow opening, explained the majority of the variance. The decrease of factor scores with increasing distance from the burrow illustrates the importance of the proximity to the burrow opening in the establishment of the factors.

Variability of the mass physical properties was determined using the coefficient of variation. Analysis indicated that, in all cases, the coefficient exceeded the reproducibility error for each property and reflected natural variation along the transects. Texture and water content were found to be the most important factors responsible for the variations in the mass physical properties, and displayed the greatest degree of correlation with changes in the other properties. The nature of the transects indicate that the observed variation is a function of distance from a burrow opening. The degree of variation was higher in Ship Harbour, suggesting that the sediments of Pirate Harbour are much more uniform in nature.

The values for the mass physical properties studied are similar to values for other near-shore, shallow subtidal environments, such as Chesapeake Bay (Harrison et al., 1964; Keller and Bennett, 1970), and Tokyo Bay (Keller and Bennett, 1970).

Strength characteristics of the subsurface sediments of the Strait of Canso have recently been conducted by Brown and Rashid (1975). They suggest that the fine-grained silts and clays found in the Strait possess a reserve resistance to stress. The ratio of undrained shear strength to existing overburden pressure (Su/Po), lies in the range

1.0 to 5.0, as shown in Figure 6-18 (Brown and Rashid, 1975). This is much higher than values for recent normally consolidated marine sediments (Bjerrum and Simons, 1960), which lie in the range of 0.17 to 0.23. Similarly, the ratio of apparent preconsolidation pressure to existing overburden pressure (Pc/Po) lies in the range 2 to 10, whereas in a recently deposited sediment the ratio would be 1.0 (Brown and Rashid, 1975). Therefore, the sediments are stronger than would be expected. However, they are still classified as very soft to soft, based on the absolute values of the shear strength (Terzaghi and Peck, 1967). Brown and Rashid (1975) attribute this reserve resistance to chemical alteration, including the effects of organic compounds.

Clay minerals in the study area are mostly chlorite and illite (Buckley et al., 1974). When attacked by organic acids, these clays release Fe, Al and other ions (Pryor, 1975). These ions will precipitate and may act as cementing agents. Brown and Rashid (1975) indicate that the clays may also be strengthened by the exchange of absorbed cations. Previously it was shown that the activity of the surface sediments adjacent to Axius burrows increases, implying an increase in the clay fraction of values such as ion exchange capacity.

Possible increase in reserve strength characteristics caused by organic agents is of interest in this study. The

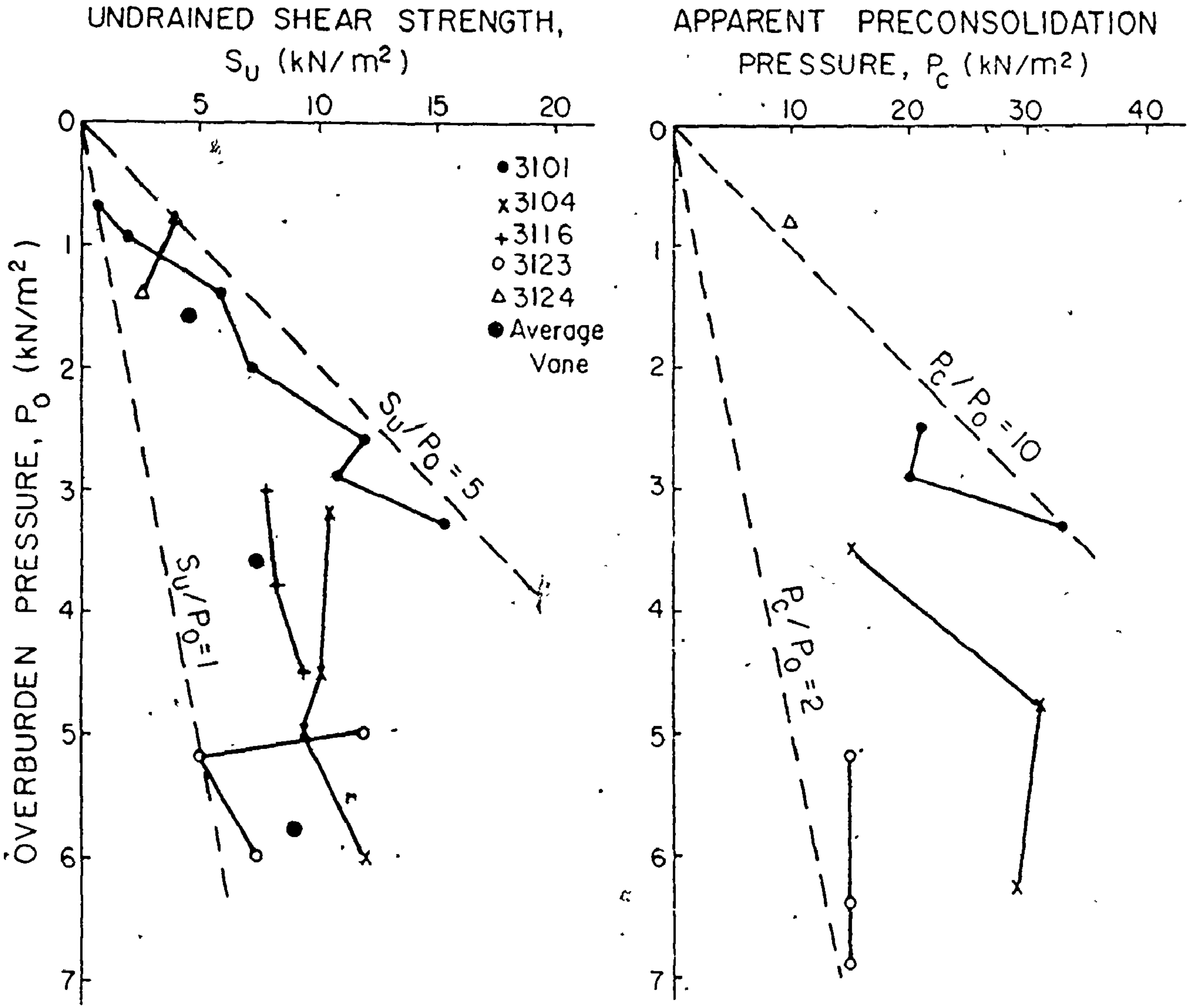


Fig. 6-18: Strength versus effective overburden pressure (after Brown and Rashid, 1975).

dissolved and particulate organic matter present in the sea is ultimately derived from:

(i) terrestrial organic debris; and

(ii) organisms living in the ocean (Degens et al., 1964).

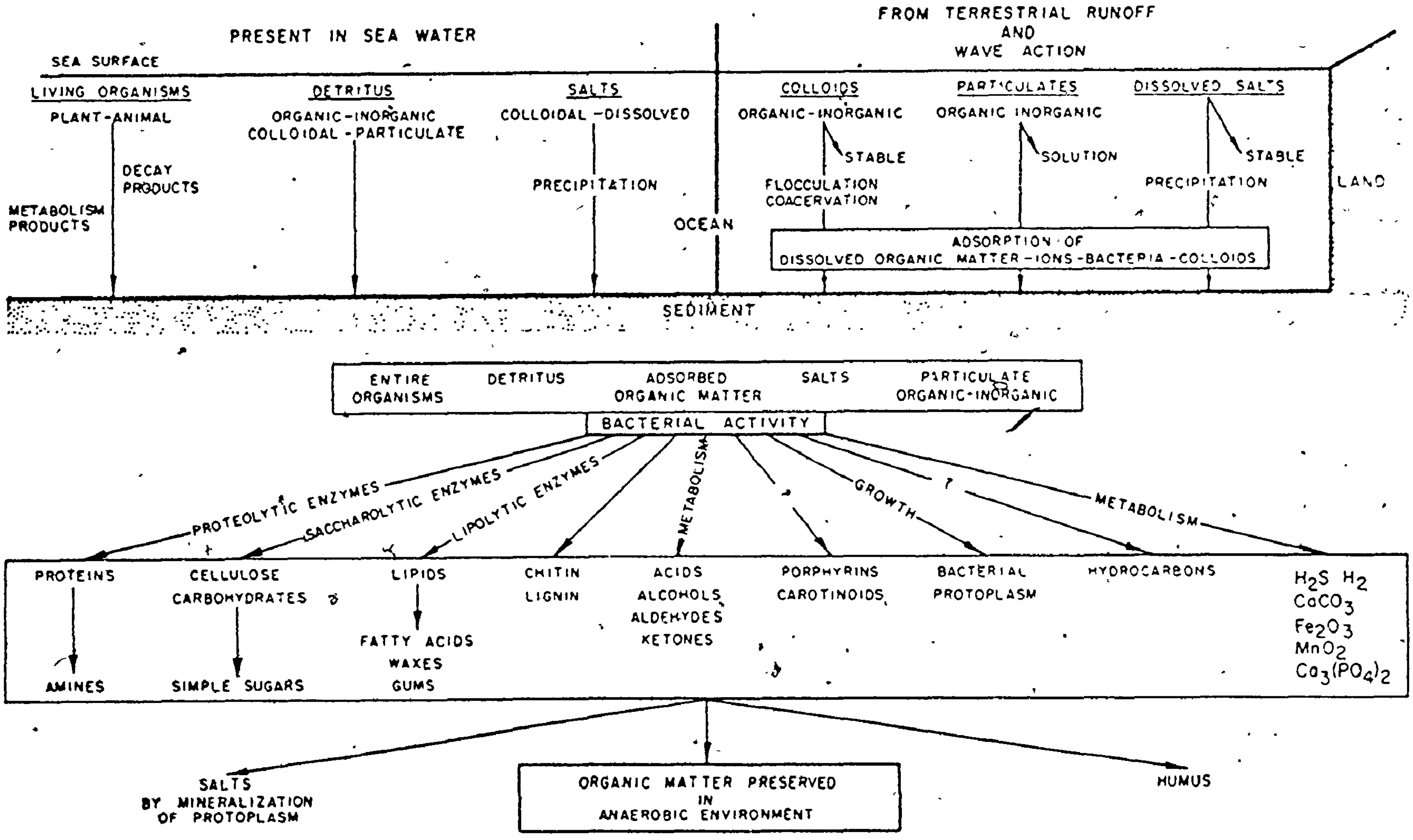
The role of bacteria in the subsequent breakdown of these organic compounds is well known (Zobell, 1946; Oppenheimer, 1960). Estimates on the abundance of bacteria in marine sediments vary from 100 million bacteria per gram (Oppenheimer, 1960) to 200 million per gram (Zhukova and Fedosov, 1963). The sediment-water interface is by far the most active zone with respect to bacterial populations, and there is a general decrease in numbers with increasing depth in the sediment (Zhukova and Fedosov, 1963).

Sediments adsorb organic material by surface attraction, and a smaller grain-size with a larger potential surface area will adsorb more organics for bacterial activity (Oppenheimer, 1960). This relationship of increasing bacterial numbers with decreasing grain-size has been confirmed by Hargrave (1972) and Dale (1974). Deposit feeders seem to feed not on the primary organic detritus (such as lignin, cellulose or chiton), but rather on the bacteria that reduce the above refactory compounds. They ingest sediment grains, crop off the bacteria and then void the grains allowing a new bacterial coating to develop (Fenchel, 1970; Newell, 1970).

The effect of bacterial action in sediments is extremely complex (Figure 6-19). When an organic residue is incorporated into a sediment, bacteria immediately begin to utilize it as a source of carbon and energy (Kononova, 1966; Martin and Haider, 1971). The plant and animal polymers, including polyaccharides, lignins and proteins, are either degraded to simple organic substances (such as water, carbon dioxide and ammonia), or metabolized into new polymers (Ehrlich, 1964; Martin and Haider, 1971). Some of the new substances form refractory complexes with metal ions or clay minerals (Kononova, 1966).

The end result of the micorbial decomposition of organic matter is the production of humic and fulvic acids, amino acids, and quinone compounds (often collectively referred to as humus), which are capable of forming organo-metallic complexes (Rashid, 1968, 1969, 1971, 1972a,b,c, 1974; Rashid et al., 1972; Rashid and King, 1969, 1970).

Burrowing organisms alter the numbers and composition of the bacterial population in a sediment. The bacterial film present at the sediment-water interface (Zobell, 1946; Oppenheimer, 1960; Zhukova and Fedosov, 1963; Renn, 1964), increases in thickness as the concentration of organics increases at the interface (Renn, 1964). Burrowing organisms increase the surface area of the sediment-



BACTERIAL ACTIVITIES IN SEDIMENTS

Fig. 6-19: Bacterial activity and by-products at the sediment water interface, (after Oppenheimer, 1960).

water interface by the creation of open burrows. Axius serratus burrows increase this area by a factor of five.

Geochemical analysis in the Strait of Canso (Buckley et al., 1974) reveals that certain ions (lead, copper, zinc and iron) have anomalous concentrations. These concentrations were found to be associated with the Axius burrows. Preliminary results have been interpreted as being due to ionic complexing by organic compounds (Rashid, personal communication). This may well explain the reserve strength characteristics displayed by the fine-grained clays in the Strait of Canso.

Examination of cores obtained by the Bedford Institute of Oceanography revealed that numerous Axius burrows were filled with surface sands. These sands are known to exhibit low bulk densities and uniform grain sizes and can be considered to be susceptible to liquefaction under vibration or shock (Brown and Rashid, 1975). In addition, other filled burrows displayed water content values and per cent mud compositions that place them in the thixotropic range proposed by Boswell (1961). Thixotropic sediment was encountered in cores 99 cm. deep. Since every core examined south of the causeway possessed Axius burrow intersections, large areas of the bottom are underlain with potentially unstable sediment.

Surface sediment from both sides of the causeway was also examined. It is known that any increase in the organic content of the sediment will increase the water-holding capacity and plasticity, by increasing the bound water of hydration, and at the same time increasing the relative mobility of individual grains (Rashid and Brown, 1975). Even small increases in the concentrations of organic matter affects the water-holding capacity of a sediment (Lambe and Martin, 1957). Surface samples from the north side of the causeway, where <u>Axius</u> has not been found, displayed much lower water contents and per cent organic carbon (Figure 6-20) than the burrowed sediments from the south side of the causeway. Samples from Ship Harbour and areas adjacent to the outfalls of the major industries, displayed per cent organic carbon up to 10%, with corresponding water contents of 90%.

Trends in the mass physical properties of the sediments of Pirate Harbour and Ship Harbour are related to the distribution of <u>Axius</u> burrows. In addition, structurally weak sediments of Ship Harbour associated with burrows of <u>Axius</u> <u>serratus</u> are unable to support the larger shelled bivalves, such as <u>Mercenaria</u>, <u>Astarte</u> and <u>Modiolus</u>.

In summary, the effects on the properties of the sediment are:

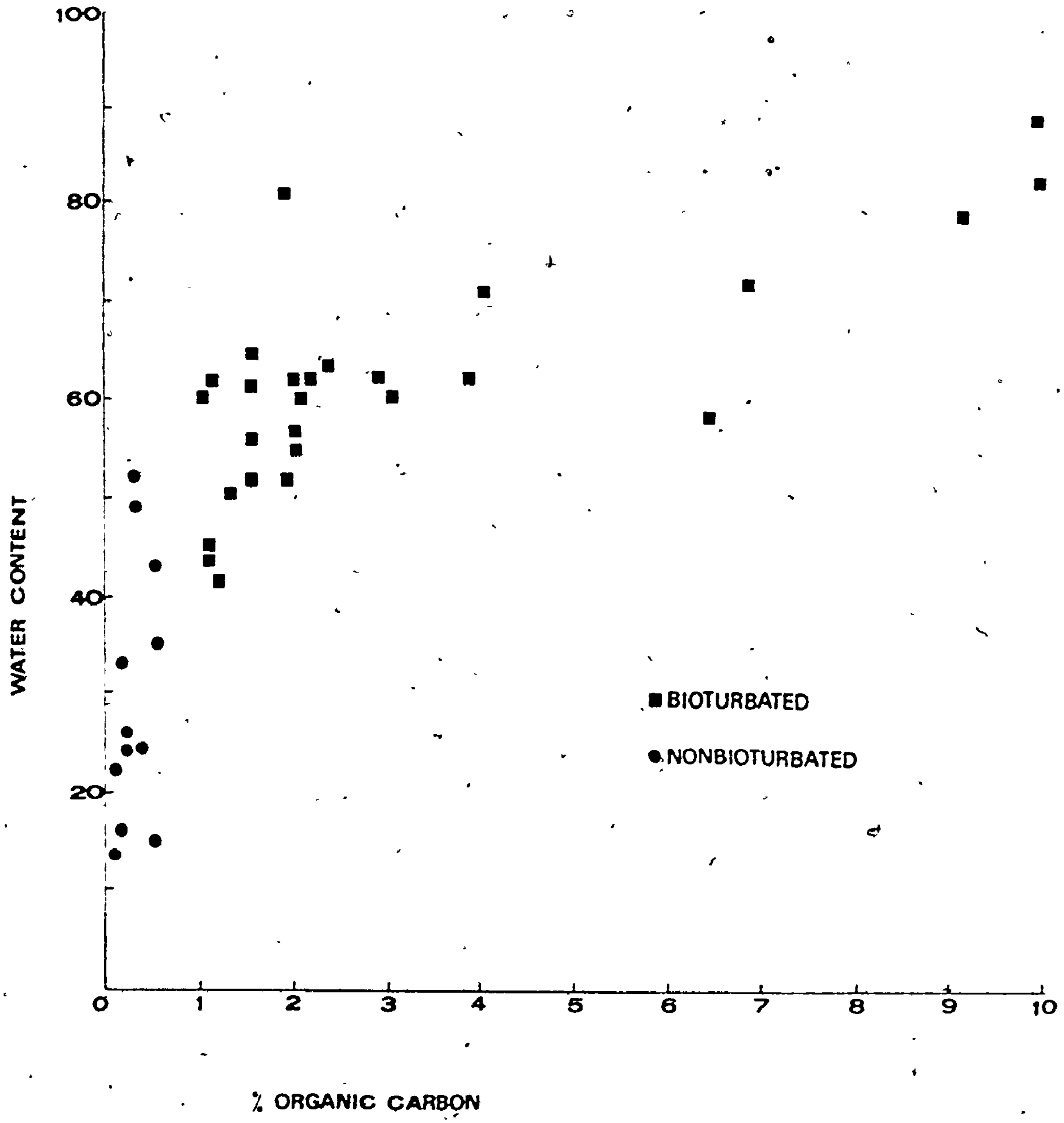


Fig. 6-20: Water content and organic carbon percent of selected samples from the Strait of Canso.

(i) the general trends of the mass physical properties with increasing distance from the burrow opening;

(ii) the introduction of unstable sands at depth;

(iii) the increase of water contents at depths resulting in thixotropic sediments;

(iv) the increase of surface water contents, which in some cases approach 172%;

(v) the increase of the area of the sediment-water interface.

CHAPTER SEVEN

SUMMARY

Recent studies of the benthic ecology of a portion of the eastern coast of Canada revealed large populations of a burrowing shrimp, of a species thought to be extremely rare. The shrimp was identified as Axius serratus Stimpson 1852, a species noted only three times from the Atlantic coast of North America. In 1954, a causeway was completed between mainland Nova Scotia and Cape Breton Island, across the Strait of Canso. Construction of the causeway altered the hydrological regime of the Strait and inadvertently created an excellent year-round deep-water harbour. Recognizing the ideal setting for port facilities, industry began to move into the area.

Investigations by SCUBA divers indicated that Axius serratus is common south of the causeway, but no shrimp burrows were identified north of the causeway. Open burrows were found in all areas studied (south of the causeway) in depths from 7.5 to 25 m., the maximum depth sampled. Burrows were abundant in the highly polluted sediments adjacent to the urban and industrialized shores, areas barren of living foraminiferas, mollusca, and ostracods. This suggests that Axius may well serve as an indicator organism of water quality.

Polyester resin casts were made of burrows, using a modification of Shinn's technique, which allows the diver to mix the resin on the bottom. One of the casts recovered is 2.9 m. long, and to the best of my knowledge represents the deepest verified bioturbation event recorded. The casts have a vertically orientated semi-circular cross-section, and in many cases were lined with eel grass, which adhered to the exterior of the casts. Studies in the spatial distribution of Axius indicated that the burrows display a uniform spacing pattern, which indicates some sort of negative interaction between individuals. It is thought that this may be related to feeding activities.

The polyester resin casts display a knobby exterior, similar to that of the trace fossil Ophiomorpha nodosa, and a re-interpretation of several crustacean ichnofossil genera is advised.

In addition to Axius, other trace-making organisms are also present in the Strait of Canso. These include the polychaetes Nereis virens and Scoloplos armiger, the nemertean Cerebratulus marginatus, and the crustacean Crangon septemspinosa. Siphons, identified as those of the bivalve Zyrphaea crispata were also found. These were of interest since Zyrphaea was not thought to range this far north. Judging from the size of the siphon, these are the largest Zyrphaea known as well as the deepest recorded burrowing depth.

The mass physical properties of the sediments of the Strait of Canso were also investigated. A number of transects were established in both Ship Harbour and Pirate Harbour, in order to examine the effect of the proximity to the burrow opening on the mass physical properties studied. As the distance from the burrow opening increased, per cent sand, per cent silt, grain density, and mass unit weight increased, and per cent clay, per cent water, liquid limit, plastic limit, plasticity index, and void ratio decreased. R-mode factor analysis and coefficient of variation, established certain relationships between the mass physical properties and illustrated the importance of the distance from the burrow opening, by explaining the majority of the variances observed in these properties.

Surface sediment south of the causeway where Axius serratus occurs contains more water and organic carbon than otherwise similar sediment north of the causeway. The sand contained in burrows at depth, in sediment cores, an unusual amount of water and can be susceptible to liquefraction under stress. Water content values measured near Axius burrows are often so high that sediment can be characterized as thixotropic. As a consequence, where Axius burrows are present, much of the sea floor is underlain, to a depth of at least 2 m. by unstable sediment-water mixtures. It was also shown that the structurally weak sediments of Ship Harbour associated with burrows of Axius serratus are unable to support the larger shelled bivalves, such as Mercenaria, Astarte, and Modiolus.

The rate of geochemical reaction reaches a maximum value at the sediment-water interface. A burrow is an extension of this interface, and the burrows in the study areas increase the area of the interface by a factor of at least 5.

REFERENCES

Ager, D. V. and Wallace, P., 1970. The distribution and significance of trace fossils in the uppermost Jurassic rocks of the Boulonnais, Northern France: *in* Trace Fossils (Crimes, T. P., and Harper, J. D., Eds.), Geol. J., Spec. Issue 3, pp. 1-18.

Ansell, A. D. and Trueman, E. R., 1967. Burrowing in *Mercenaria mercenaria*: J. Exp. Biol., V. 46, pp. 105-115.

Atkinson, R. J. A., 1974. Spatial distribution of *Nephrops* burrows. Estuarine and Coastal Mar. Sci., V. 2, pp. 171-176.

Atterberg, A., 1911. Uber die Physikalische Bodenantersuchung und uber die Plastizitat der tone. Internationale Mitteilungen fur Bodenkunde, V. 1,

Baas Becking, L. G. M. and Moore, D., 1959. Density distribution in sediments. Jour. Sed. Pet., V. 29, pp. 47-55.

Bader, R. G., 1957. A study of local variability in marine sediment. Proc. 8th Pacific Sci. Congress, 1953, V. 3, Oceanography, Nat. Research Council, Quezon, Phillipines, pp. 721-732.

Balsley, H. L., 1964. Introduction to Statistical Method. Littlefield Adams and Co., New Jersey, 347 p.

Barnes, H., and Marshall, S. M., 1951. On the variability of replicate plankton samples and some applications of caontagious series to the statistical distribution of catches over restricted periods. J. Mar. Biol. Ass. U.K., V. 30, pp. 233-263.

Bauer, E. E., 1960. History and development of the Atterberg limits tests. Am. Soc. Testing Matter, Spec. Tech. Publ., 254, pp. 160-167.

Bennett, R. H. and Keller, G. H., 1970. Mass property variability in three closely spaced deep-sea sediment cores. J. Sed. Pet., V. 40, pp. 1038-1043.

Biffar, J. A., 1971. The Genus Callianassa in South Florida, with keys to the western Atlantic Species. Bull. Mar. Sci., V. 21, pp. 627-715.

Bjerrum L., 1954. Geotechnical properties of Norwegian marine clays. Geotechnique, V. 4, pp. 49-69.

________ and Simons, H. E., 1960. Comparison of shear strength characteristics of normally consolidated clays. Proc. Res. Conf., Shear Strength in Cohesive Soils, A.S.C.E., Boulder, Colo., pp. 711-726.

Blackman, G. E., 1942. Statistical and ecological studies in the distribution of species in plant communities. I. Dispersion as a factor in the study of changes in plant populations. Ann. Bot. Lond., N.S., V. 6, pp. 351-370.

Blatt, H., Middleton, G. V. and Murray, R., 1972. Origin of Sedimentary Rocks. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 634 p.

Borradaile, L. A., 1903. On the classification of the Thalassinidea. Ann. Mag. Nat. Hist., V. 12, pp. 534-551.

Boswell, P.G.H., 1961. Muddy Sediments. Heffer Co., Cambridge, Mass. 140 p.

Braithwaite, C. J. R. and Talbot, M. R., 1972. Crustacean burrows in the Seychelles Indian Ocean. Paleogeogr. Paleoclimatol. and Paleoecol., V. 11, pp. 265-285.

Brett, C. E., 1964. A portable hydraulic diver-operated dredge sieve for sampling subtidal macro-fauna. J. Mar. Res., V. 22, pp. 205-209.

Bromley, R. G., 1967. Some observations in chalk hardgrounds. Q.J. Geol. Soc. Lond., V. 123, p. 157-182.

________ and Asgaard, U., 1972. Notes on Greenland trace fossils. II. The burrows and micro-corprolites of Glyphea rosenkrantzi, a lower Jurassic Palinuran crustacean from Jamieson Island, East Greenland. Rept. Geol. Surv. Greenland, V. 49, pp. 15-21.

________ and Frey, R. W., 1974. Redescription of the trace fossil Gyrolithes and taxonomic evaluation of Thalassinoides, Ophiomorpha and Spongeliomorpha. Bull. of Geol. Soc. Denmark, V. 23, pp. 311-335.

Brown, J. D. and Rashid, M. A., 1975. Geotechnical properties of nearshore sediments of Canso Strait, Nova Scotia. Can. Geotech. J., V. 12, pp. 44-57.

Buchanan, J. B., 1963. The biology of Calocaris macandreae. J. Mar. Biol. Ass. U.K., V. 43, pp. 729-747.

Buckley, D. E., Owens, E. H, Schafer, C. T, Vilks, G, Cranston, R. E, Rashid, M. A. Wagner, F. J. E. & Walker, D. A., 1974. Canso Strait and Chedabucto Bay. A multidisciplinary study of the impact of man on the marine environment. Geol, Sur. Can. Pap. 74-3-, V.1, pp, 133-160.

Casagrande, A., 1948. Classification and identification of soils. Am. Soc. Civil Eng. Trans., V. 113, pp. 901-931.

Cattell, R. B., 1965a. Factor Analysis: An introduction to Essentials. 1. The purpose and underlying models. Biometrics, V. 21, pp. 190-215.

_______, 1965b, 2. The role of factor analysis in research. Biometrics, V. 21, pp. 405-435.

Chamberlain, C. K., 1971. Morphology and ethology of trace fossils from the Ouachita Mountains, Southeast Oklahoma. J. Paleo., V. 45, pp. 212-246.

_______, 1975. Recent Lebensspuren in Nonmarine Aquatic Environments. in The Study of Trace Fossils (Frey, R. W. Ed.), Springer-Verlag, New York, N.Y. pp. 431-458.

Chamberlain, C. K. and Baer, J., 1973. Ophiomorpha and a new thalassinid burrow from the Permian of Utah Brigham Young Univ. Geology Studies, Y-20, pp. 79-94.

Clarke, J. H. and Evans, F. C., 1954. Distance to nearest neighbour as a measure of spatial relationships in populations. Ecol., V. 35, pp. 445-453.

________ and ________, 1935. On some aspects of spatial pattern in biological populations. Sci., V. 121, pp. 397-398.

Clarke, P. B. and Milne, A., 1955. The sublittoral fauna of the two sandy bays on the Isle of Cumbrae, Firth of Clyde. J. Mar. Biol. Ass. U.K., V. 34, pp. 61-180.

Coe, W. R., 1943. Biology of the nemerteans of the Atlantic coast of North America. Trans. Conn. Acad. Arts Sci., V. 35, pp. 129-328.

______, 1953. Resurgent populations of littoral marine invertebrates and their dependence on ocean currents and tidal currents. Ecol., V. 34, pp. 225-229.

Cole, F. and Ferguson, C., 1975. An illustrated catalogue of foraminifera and Ostracod from Canso Strait and Chedabucto Bay, Nova Scotia. Bedford Inst. Oceanog., Report Series, BI-R-75-5, 55 p.

Connell, J. H., 1956. Spatial distribution of two species of clams Mya arenaria and Petricola pholadiformis, in an intertidal area. 8th Rep. Mass. Shellfish Invest.

Connell, J. H., 1961. The influence of interspecific competition and other factors on the distribution of the barnacle Chthamalus stellatus. Ecol., V. 42, pp. 710-723.

_______, 1963. Territorial behaviour and dispersion in some marine invertebrates. Res. on Pop. Ecology, V. 2, pp. 87-101.

Cook, D. O., 1971. Depressions in shallow marine sediment made by benthic fish. J. Sed. Pet., V. 41, pp. 577-578.

Craig, H. D., 1974. Biofacies and biogenic structures of Cobequid Bay. (unpublished). McMaster University, Department of Geology, Tech. Memo. 74-1, 28 p.

Crame, J., 1941. Eastern Pacific expeditions of the New York Zoological Society. 26. Crabs of the genus Uca from the west coast of Central America. Zoologica, V. 26, pp. 145-208.

Cranston, R. E., Fitzgerald, R. A. and Winters, G. V., 1974. Geochemical data from the Strait of Canso and Chedabucto Bay, Nova Scotia. Bedford Inst. Oceanogr., Data Series, B1-D-74-3, 56 p.

Crisp, D. J., 1961. Territorial behaviour in barnacle settlement. J. Exp. Biol., V. 38, pp. 429-446.

Curran, H. A., 1976. A trace fossil brood structure of probable callianassid origin. J. Paleo., V. 50, pp. 249-259.

Dale, N. G., 1974. Bacteria in intertidal sediments. Factors related to their distribution. Limnol. and Oceanogr., V. 19, pp. 509-518.

Degens, E. T., Reuter, J. H., and Shaw, K. H. F., 1964. Biochemical composition in offshore California sediments and sea waters. Geochim. et Cosmochim. Acta, V. 28, pp. 45-66.

Dice, L. R., 1962. Measure of spacing between individuals within a population. Contr. Lab. Vert. [illegible]., Univ. Mich., V. 55, pp. 1-23.

Driscoll, E. G., 1967. Attached epifauna-substrate relations. Limnol. and Oceanogr., V. 12, pp. 633-641.

Dybern, B. I. and Hoiseter, Y., 1965. The *Nephrops norvegicus*. Sarsia, V. 21, pp. 49-55.

Ehrlich, H. L., 1964. Microbial Transformations of Minerals. *in* Principals and Applications in Aquatic Microbiol., pp. 43-61.

Einsele, G., 1967. Sedimentary processes and physical properties of cores from the Red Sea, Gulf of Aden, and the Nile Delta. *in* Marine Geotechnique, (Richards, A. F. Ed.), Univ. of Illinois Press, Urbana, pp. 154-168.

Ekdale, A. A. and Warme, J. E., 1973. A diver operated dredge for collecting quantitative benthic samples in soft sediments. J. Paleo., V. 47, pp. 1119-1121.

Elliot, G. E., 1962. More problematica from the Middle East. Micropaleontology, V. 8., pp. 29-34.

Faas, R. W., 1972. Mass physical and engineering properties of some York River sediment. Geol. Soc. Amer., Mem. 133, pp. 337-347.

Farmer, A. S. D., 1974. Burrowing behaviour of the Norway lobster Nephops norvegicus. Estuarine and Coastal Mar. Sci., V. 2, pp. 49-58.

Farrow, G. E., 1966. Bathymetric zonation of Jurassic trace fossils from the coast of Yorkshire. Paleogeog. Paleoclimatol. and Paleoecol., V. 2, pp. 103-151.

_______, 1971. Back reef and lagoonal reef environments of Aldabra Atoll distinguished by their crustacean burrows. Sym. Zool. Soc. Lond., V. 28, pp. 455-500.

Fenchel, T., 1970. Studies on the decomposition of organic detritus derived from the turtle grass, Thalassia testadinum. Limnol. and Oceanogr., V. 15, pp. 14-20.

Folk, R. L., 1974. Petrology of Sedimentary Rocks. Hemphill Publ. Co., Austin, Texas, 182 p.

Forbes, A. T., 1973. An unusual abbreviated larval life in the estuarine burrowing prawn Callianassa kraussi. Mar. Biol., V. 22, pp. 361-365.

Fothergill, H. O., 1954. Tidal circulation in the Strait of Canso. in Report of Tidal and Current Surv., Can. Hydrographic Surv., Unpubl. Manuscript, 17 p.

_______, 1955. Tidal changes in the Strait of Canso. in Rept of Tidal Current Surv., Can. Hydrographic Surv., Unpubl. Manuscript, 9 p.

Frey, R. W., 1970. Environmental significance of recent marine lebensspuren near Beaufort, North Carolina. J. Paleo., V. 44, pp. 507-519.

______, 1971. Ichnology - the study of fossil and recent lebensspuren. Louis. State Univ., Geosci., Misc. Publ., 71-1, pp. 91-125.

______ (Ed.), 1975. The Study of Trace Fossils. Springer-Verlag, New York, N. Y., 562 p.

______, Basan, P. B. and Scott, R. M., 1973. Techniques for sampling salt marsh benthos and burrows. Am. Mid. Nat., V. 89, pp. 228-234.

______ and Howard, J. D., 1969. A profile of biogenic sedimentary structures in a Holocene barrier island-salt marsh complex, Georgia. Gulf Coast Geol. Assoc., V. 19, pp. 427-444.

______ and ______, 1970. Comparison of Upper Cretaceous ichnofaunas from siliceous sandstone and chalk, Western Interior Region, U.S.A. in Trace Fossils (Crimes, T. P., and J. C. Harper Eds.), Geol. J., Sp. Issue 3, pp. 141-166.

______ and ______, 1972. Radiographic study of sedimentary structures made by beach and offshore animals in aquaria. Senckenbergiana Marit., V. 4., pp. 169-182.

______ and ______, 1975. Endobenthic adaptations of juvenile Thalassinidean shrimp. Bull. Geol. Soc. Denmark, V. 24, pp. 283-297.

Frey, R. W. and Mayou, T. V., 1971. Decapod burrows in Holocene barrier island beaches and washover fans, Georgia. Senckenbergiana Marit., V. 3, pp. 53-77.

Fursich, F. T., 1972. Thalassinoides and the origin of nodular limestone in the Corallian Beds (U. Jurassic of southern England). N. Jb. Geol. Palaont. Abh., V. 140, pp. 33-48.

————, 1973. A revision of the trace fossils *Spongeliomorpha*, *Ophiomorpha* and *Thalassinoides*. N. Jb. Geol. Palaont. Mh., V. 12, pp. 719-735.

Gage, J. and Geckie, A. D., 1973. Community structure of the benthos in Scottish Sea lochs, 2. Spatial patterns. Mar. Biol., V. 19, pp. 41-53.

Glaessner, M. F., 1948. Decapod crustaea from Eocene of Victoria. Proc. Roy. Soc. Vict., V. 59, pp. 1-7.

Gosner, K. L., 1971. Guide to the Identification of Marine and Estuarine Invertebrates. Wiley-Interscience, New York, N. Y. 693 p.

Greig-Smith, P., 1957. Quantative plant ecology. Butterworths, London, 256 p.

Gurney, R., 1937. Notes on some decapod Crustaca from the Red Sea. 1. The genus *Prolessa* 2. The larvae of *Upogebia savignyi*. Proc. Zool. Soc. Lond., (B), pp. 85-101.

————, 1942. Larvae of the decapod Crustacea. Roy. Soc. Lond., V. 129, pp. 1-306.

Hamilton, E. L., and Menard, H. W., 1956. Density and porosity of sea-floor surface sediments off San Diego, California. A.A.P.G., V. 40, pp. 754-761.

Hargrave, B. T., 1972. Aerobic decomposition of sediment and detritus as a function of particle surface area and organic content. Limnol. and Oceanogr., V. 17, pp. 583-596.

Harman, H. H., 1967. Modern Factor Analysis. Univ. Chicago Press, Chicago. 474 p.

Harrison, W., Lynch, M. P. and Altschaefal, T., 1964. Sediments of lower Chesapeake Bay with emphasis on mass properties. J. Sed. Pet., V. 34, pp. 727-755.

_______ and Wass, M. L., 1965. Frequencies of infaunal invertebrates related to water content of Chesapeake Bay sediments. Southeast Geol., V. 6, pp. 177-187.

Herreid, C., 1963. Observations on the feeding behaviour of *Cardiosoma quanhumi* in Southern Florida. Crustaceana, V. 5, pp. 176-180.

Hertweck, G., 1972. Georgia coastal region Sapelo Island: Sedimentology and Biology v. Distribution and Environmental significance of lebensspuren and *in situ* skeletal remains. Senckenbergiana Marit., V. 4, pp. 125-167.

Hertz, P., 1909. Uber den geigenseitigen durchschnittliechen Abstand von Punkten, die mit bekannter mittlerer Dichte lin Raume angeordent sind. Mathemtische Annalen, V. 67, pp. 387-398.

Hestor, N. C. and Pryor, W. A., 1972. Blade-shaped Crustacean burrows of Eocene age. A composite form of Ophiomorpha. Bull. Geol. Soc. Amer., V. 83, pp. 677-688.

Hillmer, G., 1963. Zur Okologie von Ophiomorpha. N. Jb., Geol. Palaont. Mh., 1964, pp. 137-141.

Holme, N. A., 1950. Population dispersion in Tellina tenuis. J. Mar. Biol. Assoc. U.K., V. 29, pp. 269-280.

Holmes, C. W. and Goodell, H. G., 1964. The prediction of strength in sediment of St. Andrews Bay, Florida. J. Sed. Pet., V. 24, pp. 134-143.

Howard, J. D., 1969. X-ray radiography for examination of burrowing in sediment by marine invertebrates. Sedimentology, V. 11, pp. 249-258.

________, and Frey, R. W., 1973. Characteristic physical and biological sedimentary structures in Georgia estuaries. A.A.P.G., V. 57, pp. 1169-1184.

________ and Reineck, H. E., 1972. Physical and biological sedimentary structures of the nearshore shelf, Sapelo Island, Georgia. Senckenbergiana Marit., V. 4, pp. 81-123.

Hoyt, J. H. and Weimer, R. D., 1965. The origin and significance of Ophiomorpha in the Cretaceous of the western interior. In Sym. of Sed. of L. Cret. and Tert. Outcrops, Wyoming Geol. Assoc., Guide Book, pp. 207-213.

Inderbitzen, A. L., 1970. Empirical relationships between mass physical properties for recent marine sediments off southern California. Mar. Geol., V. 9, pp. 311-329.

Johnson, P. G., 1959. Spatial distribution of Phoronopsis viridis. Sci., V. 129, p. 1221.

Jumikis, A. R., 1962. Introduction to Soil Mechanics. D. Van Nostrand Co. Inc., New Jersey.

Kaiser, H. F., 1958. The varimax criteria for analytical relation in factor analysis. Psychology, V. 23, pp. 187-200.

Kanes, W. H., 1963. Occurrence of Ophiomorpha in recent shoreface deposits, Galveston Island, Texas. (Abstract) Geol. Soc. Amer., Sp. Paper, 76, p. 89.

Karplus, I., Szelp, R. and Tsurnamal, M., 1974. The burrows of Alpheid shrimp associated with Gobiid fish in the Red Sea. Mar. Biol., V. 24, pp. 259-268.

Keij, A. H., 1965. Miocene trace fossils from Borneo. Palaont. Z., V. 39, pp. 220-228.

Keller, G. H. and Bennett, R. H., 1968. Mass physical properties of submarine sediments in the Atlantic and Pacific basins. Proc. 22nd Internat. Geol. Congress, V. 8, pp. 33-50.

________ and ________, 1970. Variations in the mass physical properties of selected submarine sediments. Mar. Geol., V. 9, pp. 215-223.

Kemper, E., 1968. Einige Bemerkungen uber die Sedimentationsverhaltnisse und die fossilen Lebensspuren des Bentheimer Sandsteins. Geol. Jb., V. 86, pp. 46-106.

Kennedy, W. J., 1967. Burrows and surface traces from the Lower Chalk of southern England. Bull. Brit. Mus., (Nat. Hist.), V. 15, pp. 127-167.

_______, 1970. Trace fossils in the chalk environment. *in* Trace Fossils (Crimes, T. P. and J. C. Harper, Eds.), Geol. J. Sp. Issue 3, pp. 263-282.

_______, Jakobson, M. E. and Johnson, R. T., 1969. A *Favreina-Thalassinoides* associated from the Great Oolite of Oxfordshire. Paleo., V. 12, pp. 549-554.

_______ and MacDougall, J., 1969. Crustacean burrows in the Weald Clay of southeast England and their environmental significance Paleo., V. 12, p. 459.

_______ and Sellwood, B. W., 1970. *Ophiomorpha nodosa*, a marine indicator from the Spagnacian of southwest England. Geol. Assoc. Proc., V. 81, pp. 99-110.

Kern, J. P. and Warme, J. E., 1974. Trace fossils and bathymetry of upper Cretaceous Point Loma Formation San Diego, California. Bull. Geol. Soc. Amer., V. 85, pp. 893-900.

Kononova, M. M., 1966. Soil Organic Matter. Pergamon, New York, N.Y. 544 p.

Kosler, A., 1968. Distributional patterns of the eulittoral fauna near the Isle of Hiddensee (Baltic Sea, Rugia). Mar. Biol., V. 1, pp. 266-268.

Krumbein, W. C., and Graybill, F. A., 1965. An Introduction to Statistical Methods in Geology. McGraw-Hill, New York, 475 p.

Lambe, T. W., 1951. Soil Testing for Engineers. J. Wiley and Sons Inc., London, 165 p.

_______ and Martin, R. T., 1957. Composition and engineering properties of soil. Proc. Highw. Res. Bd., V. 36, pp. 693-712.

Lawrence, D. J., Foster, L. A. and Loucks, R. H., 1973. Statistics of currents for navigation and dispersion in Canso Strait and Come by Chance Bay. Bedford Inst. Oceanogr., Report Series BI-R-73-6 10 p.

Levington, J. S., 1970. The paleoecological significance of opportunistic species. Lethaia, V. 3, pp. 69-78.

________, 1972. Stability and trophic structure in deposit feeding and suspension feeding communities. Am. Nat. V. 106, pp. 472-486.

________, 1974. Trophic group and evolution in bivalve molluscs. Paleo., V. 17, pp. 579-585.

MacGinite, G. E., 1930. The natural history of the mud shrimp *Upogebia*. Ann. Mag. Nat. Hist., V. 6, pp. 35-44.

________, 1934. The natural history of *Callianassa californiensis*, Amer. Midland Nat., V. 15, pp. 166-177.

MacGinite, G. E. and MacGinite, N., 1968. Natural History of Marine Animals. McGraw-Hill Co. Inc., New York, 523 p.

Martin, J. P. and Haider, K., 1971. Microbial activity in relation to soil humus formation. Soil Sci., V. 111, pp. 54-63.

Miller, D. G. and Richards, A. F., 1969. Consolidation and sedimentation compression studies on a calcareous core, Exuma Sound Bahamas. Sed., V. 12, pp. 301-316.

Moore, D. G., 1961. Submarine slumps. J. Sed. Pet., V. 31, pp. 343-357.

Newell, R., 1965. The role of detritus in the nutrition of two deposit feeders the prosobranch Hydrobia ulvae and the bivalve Macoma balthica. Proc. Zool. Soc. Lond., V. 144, pp. 25-45.

________, 1970. Biology of Intertidal Animals. American Elsevier Publ. Co., New York, 555 p.

Olmstood, F. R. and Johnston, C. M., 1955. Rapid methods for determining liquid limits of soils. Highway Res. Bd. Bull., V. 95, pp. 27-37.

Oppenheimer, C. H., 1960. Bacterial activity in sediments from shallow marine bays. Geochim. et Cosmochim. Acta, V. 19, pp. 244-26-.

Parker, R. H., 1963. Zoogeography and ecology of some macro-invertebrates particularly molluscs, in the Gulf of California and the continental slope off Mexico. Vidensk. Medd. Dansk. Naturh. Foren., V. 126, pp. 1-178.

Pearse, A. S., 1911. On the habits of Thalassina anomala. Philipp. J. Sci., V. 6, pp. 213-217.

________, 1945. Ecology of Upogebia affinis. Ecol., V. 26, pp. 303-305.

Pettibone, M. H., 1963. Marine polychaete worms of the New England region Part 1, Families Aphroditidae through Trochochaetidae. Bull. U.S. Nat. Mus., V. 227, pp. 1-356.

Pickett, T. E., Kraft, S. C. and Smith, K., 1971. Cretaceous burrows from Chesapeake and Delaware Canal. J. Paleo., V. 45, pp. 209-211.

Pohl, M. E., 1946. Ecological observations on Callianassa major, at Beaufort, North Carolina. Ecology, V. 27, pp. 71-80.

Price, K. S., 1962. Biology of the sand shrimp Crangon septemspinosa, in the shore zone of the Delaware Bay region. Chesapeake Sci., V. 3, pp. 244-255.

Pryor, W. A., 1973. Petrology and sedimentology of Ophiomorpha and modern Callianassid burrows. (Abstract), A.A.P.G., V. 57, p. 801.

________, 1975. Biogenic sedimentation and alteration of agillaceous sediment in shallow marine environments. Bull. Geol. Soc. Amer., V. 86, pp. 1244-1254.

Radwansi, A., 1970. Dependence of rock borers and burrowers on the environmental conditions within the Tortonian littoral zone of Southern Poland. in Trace Fossils, (Crimes, T.P. and J. C. Harper Eds.), Geol. J. Sp. Issue 3, pp. 371-390.

Rashid, M. A., 1969. Contribution of humic substances to the cation exchange capacity of different marine sediments. Maritime Sed., V. 5, pp. 44-50.

________, 1971. Role of humic acids of marine origin and their different molecular weight fractions in complexing di- and tri- valent metals. Soil Sci., V. 111, p. 298-306.

________, 1972a. Quinone content of humic compounds isolated from the marine environment. Soil Sci., V. 113, pp. 181-188.

________, 1972b. Role of quinone groups in solubility and complexing of metals in sediments and soils. Chem. Geol., V. 9, pp. 241-248.

________, 1972c. Amino acids associated with marine sediments and humic compounds and their role in solubility and complexing of metals. Proc. 24th Int. Geol. Congr., Montreal, Sec. 10, pp. 346-353.

________, 1974. Absorption of metals on sedimentary and peat humic acids. Chem. Geol., V. 13, pp. 115-123.

________ and Brown, J. D., 1975. Influence of marine organic compounds on the engineering properties of a remoulded sediment. Engineering Geol., V. 9, pp. 141-154.

________, Buckley, D. E. and Robertson, K. R., 1972. Interactions of a marine humic acid with clay minerals and a natural sediment. Geoderma, V. 8, pp. 11-27.

________ and King, L. H., 1969. Molecular weight distribution of humic and fulvic acid fractions from marine clays from the Scotian Shelf. Geochim. et. Cosmochim. Acta, V. 33, pp. 147-151.

Rashid, M. A. and King, L. H., 1969. Major oxygen-containing functional groups present in humic and fulvic acid fractions isolated from contrasting marine environments. Geochim. et Cosmochim. Acta, V. 34, pp. 193-201.

Rathburn, M. J., 1929. Decapoda: Canadian Atl. Fauna, V. 10, 38 p.

Rasmussen, H. W., 1971. Echinoid and crustacean burrows and diagenetic significance in the Maastrichtion-Danian of Denmark. Lethaia, V. 4, pp. 191-216.

Reineck, H. E., 1967. Layered sediment of tidal flats, beaches and shelf bottoms of the North Sea. in Estuaries (G.H. Lauff, Ed.) Publs. Am. Assoc. Advancement Sci., V. 83, pp. 191-206.

Reinson, G. E., 1975. Geochemistry of muds from a shallow restricted estuary in Australia. Mar. Geol. V. 19, pp. 297-314.

Renn. C. E., 1964. The bacteriology of the interface. in Principals and Applications in Aquatic Microbiology, pp. 193-203.

Rhoads, D. C., 1963. Rates of sediment reworking by Yoldia limatula in Buzzards Bay, and Long Island Sound. J. Sed. Pet., V. 33, pp. 727-732.

________, 1967. Biogenic reworking of intertidal and subtidal sediment in Barnstable Harbour and Buzzards Bay. J. Geol. V. 75, pp. 461-476.

________, 1970. Mass properties, stability and ecology of marine muds related to burrowing activity. in Trace Fossils (Crimes, T. P and J. C. Harper, Eds.), Geol. J. Sp. Issue 3, pp. 391-406.

Rhoads, D. C., 1973. The influence of deposit feeding benthos on water turbidity and nutrient recycling. Am. J. Sci., V. 273, pp. 1-22.

________, 1974. Organism-sediment relations on the muddy seafloor. Oceanogr. Mar. Biol. Ann. Rev., V. 12, pp. 263-300.

________ and Stanley, D. J., 1965. Biogenic graded bedding. J. Sed. Pet., V. 35, pp. 956-963.

________ and Young, D. C., 1970. The influence of deposit feeding organisms on sediment stability and community trophic structures. J. Mar. Res., V. 28, pp. 150-178.

________ and ________, 1971. Animal-sediment relations in Cape Cod Bay. 2. Reworking by Molpadia oolitica. Mar. Biol., V. 11, pp. 255-261.

Rice, A. L. and Chapman, C. S., 1971. Observations on the burrows and burrowing behaviour of two mud burrowing decapod crustaceans, Nephrops norvegicus and Goneplax rhomboides. Mar. Biol., V. 10, pp. 330-342.

Richards, A. F., 1962. Investigations of deep-sea sediment cores, 2. Mass physical properties. U.S. Naval Oceanogr. Office, Tech. Rept., Tr-106, 146 p.

________, 1962. Local sediment shear strength and water content. in Papers in Marine Geology (Miller, R. L. Ed.), Macmilliam and Co., N.Y., pp. 474-487.

Richards, A. F. Hirst, T. J., and Parks, J. M., 1974. Bulk density - water content relationships in marine silts and clays. J. Sed. Pet., V. 44, pp. 1004-1009.

_______ and Keller, G. H., 1962. Water content variability in a silty clay core from off Nova Scotia. Limnol and Oceanogr., V. 7, pp. 426-427.

_______ and Parker, H. W., 1968. Surface coring for shear strength measurements. in Civil Engineering in the Oceans. Am. Soc. Civil Engineers, New York, N. Y., pp. 445-489.

Risk, M. J. and Craig, H. D., 1976. Flatfish feeding pits. J. Sed. Pet., V. 46, pp. 411-413.

Rominger, J. F. and Rutledge, D. C., 1952. Use of soil mechanics data in correlation and interpretation of Lake Agassiz sediment. J. Geol., V. 60, pp. 160-180.

Rosfelder, A. M. and Marshall, N. F., 1967. Obtaining large, undisturbed, and orientated samples in deep water. in Marine Geotechnique (Richards, A. F. Ed.), Univ of Illinois Press, Urbana, pp. 243-263.

Salt, G. and Hollick, F. S., 1946. Studies in wireworm populations, 2. Spatial distribution. J. Exp. Biol., V. 23, pp. 1-46.

Sanders, H. L., 1958. Benthic studies in Buzzard's Bay. 1. Animal-sediment relationships. Limnol and Oceanogr., V. 3, pp. 245-258.

Sanders, H. L., 1960. Benthic studies in Buzzard's Bay, 3. The structure of the soft bottom community. Limnol and Oceanogr., V. 5, pp. 138-153.

Sankolli, K. H., 1963. On the occurrence of *Thalassina anomala*, a burrowing crustacean in Bombay waters and its burrowing methods. J. Bombay Nat. Hist. Soc., V. 60, pp. 600-605.

Schafer, W., 1972. Ecology and Paleoecology of Marine Environments. (Craig, G. Y., Ed.), Oliver and Boyd, Edinburgh, 568 p.

Scoffin, T. P., 1973. Crustacean fecal pellets *Favreina* from the middle Jurassic of Eigg, Inner Hebrides. Scott. J. Geol., V. 9, pp. 145-146.

Siedel, U., 1956. Ein vorkommen von *Ophiomorpha* in Miozan der Niederrheinischen Bucht. N. Jb. Geol. Paleont. Mh., 1956, pp. 489-493.

Seilacher, A., 1953. Studien zur Palichnologie, I. Uber die methoden der Palichnologie. N Jb. Geol. Pataont., V. 96, pp. 421-452.

_______, 1964. Biogenic Sedimentary Structures. *in* Approaches to Paleoecology (Newell, N. D., and Rigby, J. Eds), J. Wiley and Sons, New York, pp. 296-316.

_______, 1967. Bathymetry of trace fossils. Mar. Geol., V. 5, pp. 413-428.

Selbie, C. M., 1914. The decapod Repentia of the coast of Ireland, Pt. I, Palinura, Astacura and Anomura. Fisheries Ire. Sci. Invest., 1914, 1, 1. 116.

Sellwood, R. W., 1971. A Thalassinoides burrow containing the crustacean Glyphea udressieri, from the Bathonian of Oxfordshire. Paleo., V. 14, pp. 589-591.

Shaw, D. M., 1974. R-mode factor analysis on enstatitic chondrite analysis. Geochim. et Cosmochim. Acta, V. 38, pp. 1607-1613.

Shepard, F. P., 1954. Nomenclature based on sand-silt-clay ratios. J. Sed. Pet., V. 24, pp. 151-158.

Shinn, E. A., 1968. Burrowing in recent lime sediments of Florida and the Bahamas. J. Paleo., V. 42, pp. 879-894.

Simpson, S., 1975. Classification of Trace Fossils. in The study of Trace Fossils (Frey, R. W., Ed.), Springer-Verlag Inc., New York, pp. 39-54.

Skempton, A. W., 1953. The colloidal activity of clays: Proc. 3rd. Int. Conf. on Soil Mech. and Foundation Engineering, Zurich, v. 1, pp. 57-61.

Smith, S. I., 1879. The stalk eyed crustaceans of the Atlantic coast of North America, north of Cape Cod. Trans. Conn. Acad. Arts and Sci., V. 5, pp. 27-138.

Sowers, G. F., 1965. Consistency. in Methods of Soil Analysis. (Black, C. A. Ed.), No. 9, Pt. 1, Amer. Soc. of Agronomy, Madison, Wisconsin, 770 p.

Squires, H. J., 1965. Decapod crustaceans of Newfoundland, Labrador and the Eastern Arctic. Fish. Res. Bd. Can., Manuscript Rept. Ser. (Biol.), No.810, pp. 1-212.

Stanley, D. J., 1971. Fish-produced markings on the outer continental margin east of the Middle Atlantic States. J. Sed. Pet., V. 41, pp. 159-170.

Stanton, R. J. and Warme, J. E., 1971. Stop 1, Stone City Bluff. Louisiana State Univ., Geosci., Mics. Publ., 71-1, pp. 27-43.

Stevens, B., 1929. Ecological observations on Callianassidae of Puget Sound. Ecol., V. 10, pp. 399-405.

Stimpson, W., 1852. A description of new crustacean belonging to the genus Axius. Proc. Boston Soc. Nat. Hist., V. 4, pp. 221-223.

Teal, J. M., 1958. Distribution of fiddler crabs in Georgia salt marshes. Ecol., V. 39, pp. 185-193.

Terzaghi, L., 1963. Theoretical Soil Mechanics. Wiley, New York, 510 p.

________ and Peck, R. B., 1967. Soil Mechanics in Engineering Practise. Wiley, New York, 729 p.

Thayer, C. W., 1975. Morphological adaptations of benthic invertebrates to soft sediments. J. Mar. Res., V. 33, pp. 177-189.

True, M. A., Reys, J. P. and Delauze, H., 1968. Progress in sampling the benthos; the benthic suction dredge. Deep-Sea Res., V. 15, pp. 239-242.

Turpaeva, E. P., 1959. Food interrelationships of dominent species in marine benthic biocenoses. in Marine Biology (Nikitin, B. N. Ed.) Trans. Inst. Ocean., 20, pp. 137-148.

Vilks, G., Schafer, C. T. and Walker, D. A., 1975. The influence of a causeway on oceanography and foraminifera in the Strait of Canso. Can. J. Earth Sci., V. 12, pp. 2086-2102.

Wagner, F. J. E., 1975. Mollusca of the Strait of Canso area. Geol. Surv. Can. Paper 75-23, 29 p.

Warme, J., 1967. Graded bedding in the recent sediments of Mugu Lagoon, California. J. Sed. Pet., V. 37, pp. 540-547.

Weber, W. G. and Kleiman, W. F., 1960. Moisture and strength variation in a thick, uniform clay layer, in Papers on Soil, 1959 Meetings, Philadelphia, Penn., ASTM., Sp. Tech. Publ., 254, pp. 284-295.

Weimer, R. J. and Hoyt, J. H., 1964. Burrows of Callianassa major, geological indicators of littoral and shallow neritic environments. J. Paleo., V. 38, pp. 761-767.

Weis, J. J., 1976. Effects of environmental factors on regeneration and molting in fiddler crabs. Biol. Biol. Bull., V. 150, pp. 152-162.

Whiteaves, J. F., 1874. On recent deep-sea dredging operatings in the Gulf of St. Lawrence. Amer. J. Sci., Ser. 3, V. 7, pp. 210-219.

Williams, A. B., 1965. Marine decapod crustaceans of the Carolinas. U.S. Fish. Bull., V. 65, pp. 1-298.

Winston, J.E. and Anderson, F. E., 1971. Bioturbation of sediment in a northern temperate estuary. Mar. Geol., V. 10, pp. 39-49.

Wisely, H. B., 1960. Observation on the settling behaviour of larvae of the tube worm *Spirorbis borealis*. Aust. J. Mar. and Freshwater Res., V. 11, pp. 55-72.

Yong, R. H. and Warkentin, B. P., 1975. Soil Properties and Behaviour. Elsevier, Amsterdam, 449 p.

Zhukova, A. I. and Fedosov, M. V., 1963. Significance of microorganisms of the upper sediment layer of shallow water basins, in the transformation of organic matter. in Marine Microbiology, (Oppenheimer, C. H. Ed.), pp. 711-719.

Ziegelneimer, E., 1954. Beobachtunger uber den Nahrungserwerb bei der Naticide *Lunatia nitida*. Helgol. wiss. Meeresuntersuch, V. 5, pp. 1-33.

Zobell, C. E., 1946. Marine Microbiology. Chronica Botanica Watham, Mass., 240 p.

TABLE 6-3: MASS PHYSICAL PROPERTIES OF SEDIMENTS FROM PIRATE HARBOUR, STRAIT OF CANSO

Transect Number	Sample Number	Dist. from burrow (cm)	Sand %	Silt %	Clay %	Sediment type (Shepard, 1954)	Mass Unit Weight (g/cm^3)	Grain Density (gs)	Void Ratio (e)	Porosity (n)
1	1-1	0	4	50	46	Clayey silt	1.43	2.64	2.93	74.5
	1-2	30	12	46	42	Clayey silt	1.46	2.63	2.63	72.4
	1-3	60	10	54	36	Clayey silt	1.49	2.63	2.36	70.3
	1-4	90	15	52	33	Clayey silt	1.52	2.64	2.22	68.8
	1-5	180	30	36	34	Sand-Silt-Clay	1.57	2.64	1.96	66.2
	1-6	0	5	46	39	Clayey silt	1.96	2.63	2.6	72.2
	1-7	30	22	39	39	Sand-Silt-Clay	1.54	2.63	2.11	67.8
	1-8	60	25	39	36	Sand-Silt-Clay	1.56	2.64	1.97	66.3
	1-9	90	25	45	30	Sand-Silt-Clay	1.59	2.64	1.87	65.1
	1-10	180	34	40	26	Sand-Silt-Clay	1.63	2.65	1.68	62.7
2	2-1	0	4	53	43	Clayey silt	1.42	2.62	2.96	74.8
	2-2	30	7	53	40	Clayey silt	1.46	2.63	2.66	72.7
	2-3	60	16	42	40	Clayey silt	1.49	2.63	2.43	70.8
	2-4	90	19	46	35	Clayey silt	1.52	2.64	2.25	69.1
	2-5	160	32	31	37	Sand-Silt-Clay	1.56	2.64	2.02	66.9
	2-6	0	16	49	35	Clayey silt	1.46	2.63	2.64	72.5
	2-7	30	19	48	33	Clayey silt	1.51	2.63	2.28	69.3
	2-8	60	26	35	39	Sand-Silt-Clay	1.55	2.64	2.08	67.6
	2-9	90	21	45	34	Sand-Silt-Clay	1.56	2.64	2	66.7
	2-10	160	32	38	30	Sand-Silt-Clay	1.61	2.64	1.74	63.5
3	3-1	0	8	47	45	Clayey silt	1.43	2.62	2.83	73.9
	3-2	30	14	49	37	Clayey silt	1.47	2.63	2.57	72
	3-3	60	19	49	32	Clayey silt	1.5	2.64	2.35	70.1
	3-4	90	20	50	30	Sand-Silt-Clay	1.54	2.64	2.11	67.9
	3-5	150	35	35	30	Sand-Silt-Clay	1.55	2.64	2.04	67.1

R, STRAIT OF CANSO

ype 954)	Mass Unit Weight (g/cm^3)	Grain Density (gs)	Void Ratio (e)	Porosity (n)	Activity (Ac)	Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)	Liquidity Index (LI)	Water Content (W)
	1.43	2.64	2.93	74.5	.76	78	43	35	1.83	107
	1.46	2.63	2.63	72.4	.74	69	38	31	1.9	97
	1.49	2.63	2.36	70.3	.89	71	39	32	1.56	89
	1.52	2.64	2.22	68.8	.91	69	38	30	1.43	81
ey	1.57	2.64	1.96	66.2	.88	71	54	24	1.57	71
	1.96	2.63	2.6	72.2	.89	68	33	35	1.77	95
ay	1.54	2.63	2.11	67.8	.82	57	25	32	1.63	77
lay	1.56	2.64	1.97	66.2	.83	55	25	30	1.6	73
lay	1.59	2.64	1.87	65.1	1.07	54	22	32	1.44	68
lay	1.63	2.65	1.68	62.7	.96	50	25	25	1.44	61
	1.42	2.62	2.96	74.8	.69	75	45	30	2.13	109
	1.46	2.63	2.66	72.7	.9	72	36	36	1.72	98
	1.49	2.63	2.43	70.8	.83	68	35	33	1.64	89
	1.52	2.64	2.25	69.1	.97	70	36	34	1.35	82
ay	1.56	2.64	2.02	66.9	.86	57	25	32	1.53	74
	1.46	2.63	2.64	72.5	1	69	34	35	1.8	97
	1.51	2.63	2.28	69.3	1.06	65	30	35	1.54	84
ay	1.55	2.64	2.08	67.6	.79	57	26	31	1.61	76
ay	1.56	2.64	2	66.7	.97	58	25	33	1.45	73
ay	1.61	2.64	1.74	63.5	.93	53	25	28	1.36	63
	1.43	2.62	2.83	73.9	.82	77	40	37	1.73	104
	1.47	2.63	2.57	72	.81	65	35	30	1.97	94
	1.5	2.64	2.35	70.1	1.03	69	36	33	1.53	86
ay	1.54	2.64	2.11	67.9	1.2	66	30	36	1.31	77
ay	1.55	2.64	2.04	67.1	1.1	55	22	23	1.61	75

TABLE 6-4 MASS PHYSICAL PROPERTIES OF SEDIMENTS FROM SHIP HARBOUR, STRAIT OF CANSO

Transect Number	Sample Number	Dist. from burrow (cm)	Sand %	Silt %	Clay %	Sediment type (Shepard, 1954)	Mass Unit Weight (g/cm^3)	Grain Density (gs)	Void Ratio (e)	Porosity (n)
13	13-1	0	10	30	60	Silty clay	1.29	2.49	4.36	81.4
	13-2	30	17	28	55	Silty clay	1.33	2.49	3.58	78.2
	13.3	60	18	33	49	Silty clay	1.37	2.50	3.14	75.8
	13.4	90	19	35	46	Silty clay	1.38	2.51	3.06	75.4
	13-5	180	9	48	43	Clayey silt	1.50	2.55	2.2	68.7
	13.6	0	4	32	64	Silty clay	1.30	2.49	4.05	80.2
	13-7	30	15	35	50	Silty clay	1.37	2.50	3.16	75.9
	13-8	60	15	29	56	Silty clay	1.38	2.51	3.05	75.3
	13-9	90	33	17	50	Silty clay	1.4	2.54	2.97	74.8
	13-10	180	8	57	35	Clayey silt	1.53	2.55	2.02	66.8
14	14-1	0	5	28	67	Silty clay	1.28	2.48	4.4	81.5
	14-2	30	10	25	65	Silty clay	1.33	2.49	3.64	78.4
	14-3	60	4	31	65	Silty clay	1.36	2.50	3.33	76.9
	14-4	90	8	33	59	Silty clay	1.37	2.51	3.16	75.9
	14-5	170	17	45	38	Clayey silt	1.48	2.54	2.3	69.7
	14-6	0	7	31	62	Silty clay	1.29	2.49	4.15	80.6
	14-7	30	10	34	56	Silty clay	1.36	2.50	3.24	76.4
	14-8	60	11	35	54	Silty clay	1.38	2.51	3.09	75.6
	14-9	90	11	40	49	Silty clay	1.39	2.52	2.97	74.8
	14-10	170	17	50	33	Clayey silt	1.52	2.55	2.06	67.3
15	15-1	0	33	31	66	Silty clay	1.29	2.48	4.33	81.2
	15-2	33	8	33	59	Silty clay	1.34	2.49	3.45	77.5
	15-3	66	12	35	53	Silty clay	1.37	2.50	3.17	75.9
	15-4	99	15	32	53	Silty clay	1.38	2.51	3.11	75.7
	15-5	205	10	50	40	Clayey silt	1.51	2.55	2.15	68.2

UR, STRAIT OF CANSO

Mass Unit Weight (9/cm^3)	Grain Density (gs)	Void Ratio (e)	Porosity (n)	Activity (Ac)	Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)	Liquidity Index (LI)	Water Content (W)
1.29	2.49	4.36	81.4	1	105	45	60	2.08	170
1.33	2.49	3.58	78.2	1.02	102	46	56	1.66	139
1.37	2.50	3.14	75.8	1.27	109	47	62	1.21	122
1.38	2.51	3.06	75.4	1.12	92	41	51	1.51	109
1.50	2.55	2.2	68.7	.84	88	31	36	1.44	83
1.30	2.49	4.05	80.2	1.03	101	35	66	1.86	158
1.37	2.50	3.16	75.9	1.04	88	35	52	1.65	122
1.38	2.51	3.05	75.3	.96	85	36	54	1.61	118
1.4	2.54	2.97	74.8	.96	84	31	48	1.6	113
1.53	2.55	2.02	66.8	.94	56	27	25	1.52	78
1.28	2.48	4.4	81.5	1	110	43	67	1.93	172
1.33	2.49	3.64	78.4	.98	101	37	64	1.64	142
1.36	2.50	3.33	76.9	1	105	40	65	1.37	129
1.37	2.51	3.16	75.9	1.05	100	38	62	1.35	122
1.48	2.54	2.3	69.7	1.03	67	28	39	1.51	87
1.29	2.49	4.15	80.6	1.08	105	38	67	1.84	161
1.36	2.50	3.24	76.4	.98	89	34	55	1.65	125
1.38	2.51	3.09	75.6	1.02	86	31	55	1.6	119
1.39	2.52	2.97	74.8	1.1	87	33	54	1.5	144
1.52	2.55	2.06	67.3	.76	52	27	25	2.04	78
1.29	2.48	4.33	81.2	1.03	110	42	68	1.87	169
1.34	2.49	3.45	77.5	1.08	100	36	64	1.53	134
1.37	2.50	3.17	75.9	1.26	109	42	67	1.21	123
1.38	2.51	3.11	75.7	1.06	96	40	56	1.41	118
1.51	2.55	2.15	68.2	.7	54	26	28	1.96	81

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TABLE 6-12:

MASS PHYSICAL PROPERTIES AND COEFFICIENTS OF VARIATION (V%) OF SEDIMENT FROM SHIP HARBOUR

A· Surface Sediments

Transect	SAND %						SILT %						CLAY %						WATER CONTENT % d				
	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5
13	10	17	18	19	9	69	30	28	33	35	48	58	60	55	49	46	43	34	170	139	122	118	[illegible]
14	5	10	4	8	17	136	28	25	35	33	45	60	67	65	65	38	38	49	172	142	129	122	8
15	3	8	12	15	10	125	31	33	35	32	50	53	66	59	53	53	40	48	169	134	123	119	8

	PLASTICITY INDEX						LIQUIDITY INDEX						GRAIN DENSITY						VOID RATIO				
	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5
13	60	56	62	51	36	49	2.08	1.66	1.21	1.51	1.44	55	2.49	2.49	2.50	2.51	2.55	2.4	4.36	3.58	3.14	3.06	2
14	67	64	65	62	39	47	1.93	1.64	1.37	1.35	1.51	37	2.48	2.49	2.50	2.51	2.54	2.4	4.4	3.64	3.33	3.16	2
15	68	64	67	56	28	70	1.87	1.53	1.21	1.41	1.96	47	2.48	2.49	2.50	2.51	2.55	2.4	4.33	3.45	3.17	3.11	2

B Surface Sediments··Core depth 20 cm

	SAND %						SILT %						CLAY %						WATER CONTENT % dr				
	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5
13	4	15	15	33	8	193	32	35	29	17	57	118	64	50	56	50	35	57	158	122	118	113	76
14	7	10	11	11	17	89	31	34	35	40	50	50	62	66	54	49	33	57	161	125	119	114	78

	PLASTICITY INDEX						LIQUIDITY INDEX						GRAIN DENSITY						VOID RATIO				
	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5
13	66	52	54	48	33	65	1.86	1.65	1.61	1.6	1.52	20	2.49	2.5	2.51	2.54	2.55	2.4	4.05	3.16	3.05	2.97	2.
14	67	55	55	54	35	82	1.84	1.65	1.6	1.5	2.04	12	2.49	2.5	2.51	2.52	2.55	2.4	4.15	3.24	3.09	2.87	2.

DIMENT FROM SHIP HARBOUR

	CLAY %						WATER CONTENT % dry weight						LIQUID LIMIT						PLASTIC LIMIT					
	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V
8	60	55	49	46	43	34	170	139	122	118	83	69	105	102	109	92	67	40	45	46	47	41	31	35
0	67	65	65	39	38	49	172	142	129	122	87	65	110	101	105	100	67	45	43	37	40	39	28	40
3	66	59	53	53	40	48	169	134	123	119	81	70	110	100	109	96	54	60	42	36	42	40	26	43

	GRAIN DENSITY						VOID RATIO						SATURATED UNIT WEIGHT						ACTIVITY					
	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V
5	2.49	2.49	2.50	2.51	2.55	2.4	4.36	3.58	3.14	3.06	2.2	66	1.29	1.33	1.37	1.38	1.5	15	1	1.02	1.27	1.12	.04	4
7	2.48	2.49	2.50	2.51	2.54	2.4	4.4	3.64	3.33	3.16	2.3	62	1.28	1.33	1.36	1.37	1.49	15	1	.98	1	1.05	1.02	7
7	2.48	2.49	2.50	2.51	2.55	2.4	4.33	3.45	3.17	3.11	2.15	67	1.29	1.34	1.37	1.38	1.51	16	1.03	1.08	1.26	1.06	.7	55

	CLAY %						WATER CONTENT % dry weight						LIQUID LIMIT						PLASTIC LIMIT					
V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V
118	64	50	56	50	35	57	158	122	118	113	76	70	101	88	85	84	56	54	35	36	31	36	26	31
50	62	66	54	49	33	57	161	125	119	114	78	70	105	89	86	77	52	63	38	34	31	33	27	34

	GRAIN DENSITY						VOID RATIO						SATURATED UNIT WEIGHT						ACTIVITY					
V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V
20	2.49	2.5	2.51	2.54	2.55	2.4	4.05	3.16	3.05	2.97	2.02	67	1.3	1.37	1.38	1.4	1.53	16	1.03	1.04	.96	.96	.94	10
12	2.49	2.5	2.51	2.52	2.55	2.4	4.15	3.24	3.09	2.87	2.06	68	1.3	1.36	1.38	1.39	1.52	16	1.08	.98	1.02	1.1	.76	35

TABLE 6-13:

MASS PHYSICAL PROPERTIES AND COEFFICIENTS OF VARIATION (V%) OF SEDIMENT FROM PIRATE HARBOUR

A Surface Sediments

Transect	SAND %						SILT %						CLAY %						WATER CONTENT % dr				
	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5
1	4	12	10	15	30	183	50	46	54	52	36	38	46	42	36	33	34	26	107	97	89	81	71
2	4	7	18	19	32	197	53	53	42	46	31	49	43	40	40	35	37	21	109	98	89	82	74
3	8	14	19	20	35	141	47	49	49	50	35	33	45	37	32	30	30	73	104	94	86	77	75

	PLASTICITY INDEX						LIQUIDITY INDEX						GRAIN DENSITY						VOID RATIO				
	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5
1	35	31	32	30	30	16	1.83	1.9	1.56	1.43	1.57	28	2.64	2.63	2.63	2.64	2.64	.39	2.93	2.63	2.36	2.22	1
2	30	36	33	34	32.	19	2.13	1.72	1.64	1.35	1.53	47	2.62	2.63	2.63	2.64	2.64	.76	2.96	2.66	2.43	2.25	2
3	37	30	33	36	33	21	1.73	1.97	1.53	1.31	1.61	41	2.62	2.63	2.64	2.64	2.64	.76	2.83	2.57	2.35	2.11	2

B Subsurface Sediments Core Depth 20 cm

	SAND %						SILT %						CLAY %						WATER CONTENT % d				
	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5
1	5	22	25	25	25	131	46	39	39	45	40	17	39	39	36	30	26	38	95	77	73	68	61
2	16	19	26	21	32	20	49	48	35	45	38	33	35	33	39	34	30	26	97	84	76	73	63

	PLASTICITY INDEX						LIQUIDITY INDEX						GRAIN DENSITY						VOID RATIO				
	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5
1	35	32	30	32	25	33	1.77	1.63	1.6	1.44	1.44	21	2.63	2.63	2.64	2.64	2.65	.76	2.6	2.11	1.97	1.87	1.
2	35	35	31	33	28	22	1.8	1.54	1.61	1.45	1.61	28	2.63	2.63	2.64	2.64	2.64	.4	2.64	2.28	2.08	2	1.

DIMENT FROM PIRATE HARBOUR

CLAY %						WATER CONTENT % dry weight						LIQUID LIMIT						PLASTIC LIMIT					
1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V
46	42	36	33	34	26	107	97	89	81	71	41	78	69	71	68	54	35	43	38	39	38	24	52
43	40	40	35	37	[illegible]	109	98	89	82	74	39	75	72	68	70	57	26	45	36	35	36	25	57
45	37	32	30	30	73	104	94	86	77	75	33	77	65	69	66	55	33	40	35	36	30	22	55

GRAIN DENSITY						VOID RATIO						SATURATED UNIT WEIGHT						ACTIVITY					
1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V
2.64	2.63	2.63	2.64	2.64	.39	2.93	2.63	2.36	2.22	1.96	40	1.43	1.46	1.49	1.52	1.57	9	.76	.74	.89	.91	.98	20
2.62	2.63	2.63	2.64	2.64	.76	2.96	2.66	2.43	2.25	2.02	38	1.42	1.46	1.49	1.52	1.56	9	.69	.9	.83	.97	.86	33
2.62	2.63	2.64	2.64	2.64	.76	2.83	2.57	2.35	2.11	2.04	33	1.43	1.47	1.50	1.54	1.55	8	.82	.81	1.03	1.2	1.1	39

	CLAY %						WATER CONTENT % dry weight						LIQUID LIMIT						PLASTIC LIMIT					
	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V
17	39	39	36	30	26	38	95	77	73	68	61	46	68	57	55	54	50	32	33	25	25	22	25	42
33	35	33	39	34	30	26	97	84	76	73	63	43	69	65	57	58	53	27	34	30	26	25	25	32

	GRAIN DENSITY						VOID RATIO						SATURATED UNIT WEIGHT						ACTIVITY					
	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V	1	2	3	4	5	V
21	2.63	2.63	2.64	2.64	2.65	.76	2.6	2.11	1.97	1.87	1.68	45	1.46	1.54	1.56	1.59	1.63	11	.89	.82	.83	1.07	.96	27
28	2.63	2.63	2.64	2.64	2.64	.4	2.64	2.28	2.08	2	1.74	42	1.46	1.51	1.55	1.56	1.61	10	1.	1.06	.79	.97	.93	29