Transport And Destruction Of Pelecypod Valves In The Minas Basin, Bay Of Fundy.

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By

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A Thesis Submitted To The

Department Of Geology

McMaster University

May, 1975.

Bachelor of Science (1974) McMaster University

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TITLE: Transport And Destruction Of Pelecypod Valves In The Minas Basin, Bay Of Fundy.

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NUMBER OF PAGES: x, 61.

Abstract

Processes affecting the transportation and destruction of empty valves of the pelecypods Mya arenaria and Macoma balthica, were examined within the intertidal zone off Portapique Beach in the Minas Basin(Bay of Fundy). It was found that valve transport was away from shore within channels and eastward alongshore on the flats. It was observed that the rate of transport of left valves and small valves was greater than right valves large valves respectively. Transported valves are preferential oriented by currents of the flood and ebb tides and those within intertidal channels. Channel migration does not appear to be of significance in removing empty valves from these intertidal sediments. The loss valves from within the sediment is attributed to an unknown 'escape' mechanism. Once free of the sediment, valves are transported, weakened by boring thallophytes and mechanically destroyed during transport.

Acknowledgements

The author wishes to thank his thesis supervisor Dr. M. J. Risk for his constant assistance and guidance. Thanks go to Mr. James Moffat for his helpful discussions concerning the study area, and to Mr. Michael Beattie with whom each new idea was tested. Special thanks go to Miss Colleen McDonald who assisted the author in the field, listened with enthusiasm to each new idea, and who deciphered the authors notes and typed both the rough and the final copies of the manuscript.

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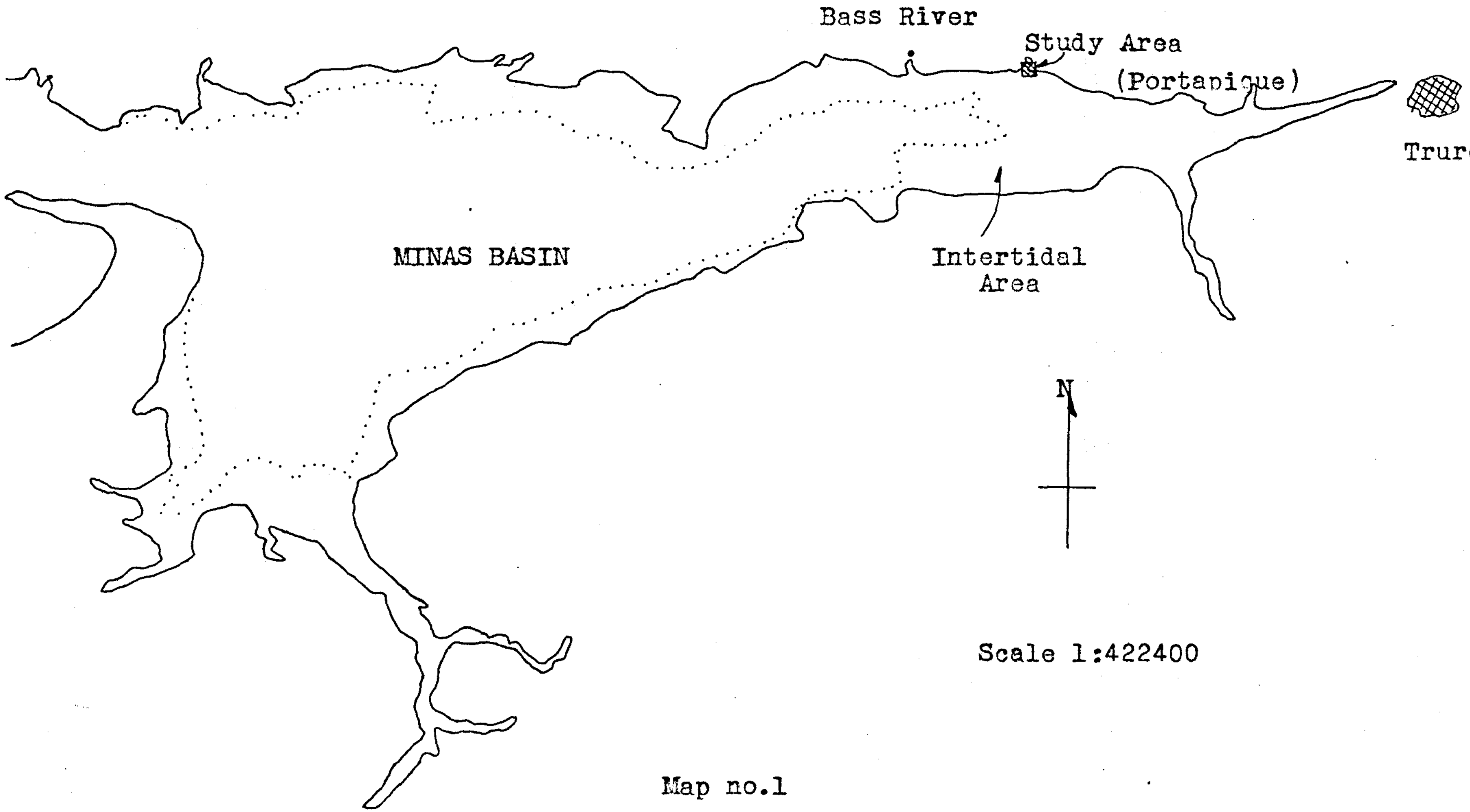
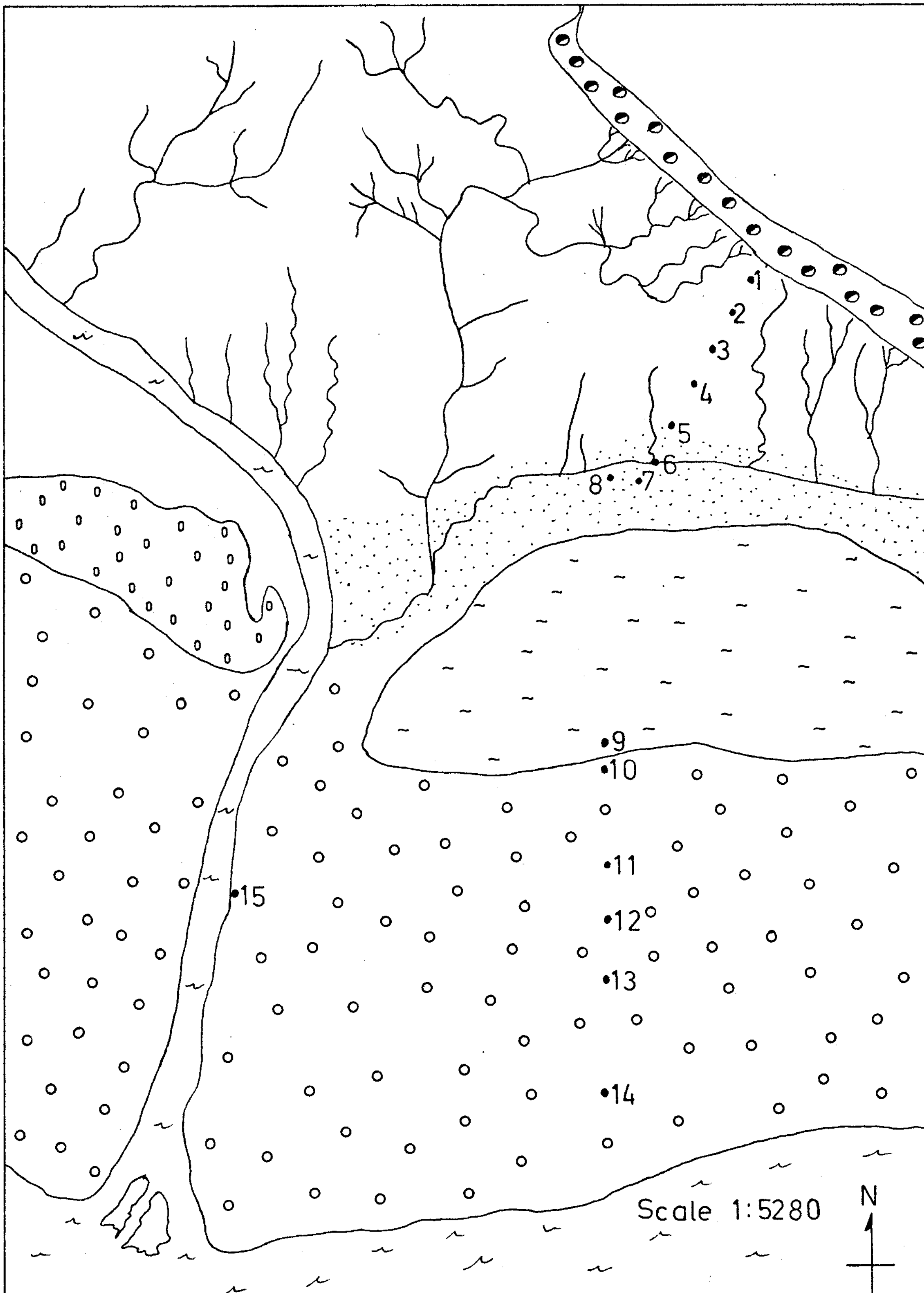


Map no.1

MINAS BASIN, NOVA SCOTIA



Map No. 2 Portapique Beach

INTRODUCTION

During the first week of August, 1974, the author had the opportunity to conduct research in the intertidal of the Minas Basin (Bay of Fundy). The purpose of this research was to investigate the processes that affect the distribution of empty valves of the pelecypods *Mya arenaria* and *Macoma balthica* in the intertidal zone. Portapique Beach was selected as the study area (Map #1 and #2), because it contained many different substrates. These varied from nearshore mudflats, sand flats, bedrock outcrop (Triassic redbeds) to offshore cobbleflats. A variety of different-sized intertidal channels were also present. The study area was considered representative of Minas Basin intertidal habitats.

Many physical, chemical, and biological factors affect empty pelecypod valves in intertidal areas. These include the distribution of live pelecypods, tidal currents, intertidal channels, shell breakage (abrasion), shell dissolution, and attack by boring thallophytes. In any one area, the distribution and characteristics of empty valves is dependant upon the relative importance of these factors.

The processes affecting pelecypod valve transport, destruction, and deposition have been discussed in the literature. Topics discussed have included field studies of the movement, orientation, abrasion and sorting of pelecypod valves in many marine environments. The labratory studies have investigated similar factors, and have attempted to quantify the effects of many of these. Qualitative discussions of shell dissolution, breakage (abrasion) and attack by microrganisms are also present in the literature. A comprehensive bibliography of the existing literature pertaining to these topics can be found in the list of references.

Thus many of the processes affecting the distribution and characteristics of empty pelecypod valves in marine environment have been studied to varying degrees. Few of these studies have been conducted in intertidal areas, and studies of more than a few of these processes have not been attempted in any one study area. Therfore, the purpose of this study is to investigate many of the processes which affect the transportation, destruction, and deposition of pelecypod valves in the intertidal zone of Portapique Beach (Map No. 2).

PELECYPOD VALVE DISTRIBUTION, TRANSPORT AND BREAKAGE IN THE STUDY AREA

A study of the processes affecting the distribution, transportation and breakage of shells, should begin with a discussion of the distribution of empty valves within the study area. The distribution of live pelecypods (Mya arenaria and Macoma balthica) within intertidal areas is well documented in the biological and ecological literature (Lammens, 1967, Winston and Anderson, 1971, Newell, 1965, Brafield and Newell, 1961). Distribution of empty pelecypod valves commonly receives less attention. Since most pelecypods preserved in ancient sediments are seldom in "life" position, studies of post-mortem processes are necessary.

There is a general lack of empty valves on the surface of sediment in intertidal areas. Concentrations may exist in the form of shell banks and lags (Schafer, 1972), but these were not present in the study area. The number of valves seen in intertidal channels appeared to be greater than the number upon the sediment surface. Local groups of empty valves appeared to display a preferred orientation.

To determine the effect of the various forces acting upon empty valves, marked valves were placed in various intertidal environments of the study area. Two transects, offset at the middle, were established from the "break of slope' at the beach, to the low tide mark (Map #2). Secondary stations were also established at various other locations. These stations were situated within intertidal channels and beside intertidal channels. In this way, the 'experimental' valves could be observed at intervals, to determine their direction and amount of movement. These data might the define valve movement, and suggest the relative influence of various forces throughout the study area.

Data were also obtained by observing the distribution and disposition of 'natural' valves, and the collection of these for further study in the laboratory. Flume studies were conducted with these valves, to determine the hydrodynamic properties of empty pelecypod valves of Mya arenaria and Macoma balthica. A correlation between the 'experimental' valve data (field, laboratory, and flume) and the 'natural' valve data (distribution and disposition) might lead to an understanding of the processes at work.

VALVE TRANSPORT EXPERIMENTS-INTRODUCTION

Several experiments were conducted to study the direction and magnitude of shell transport, upon the intertidal flats and within intertidal channels. The experiments were based upon the observation of 'marked' valves. The experimental valves of Mya arenaria and Macoma balthica were painted and numbered for identification purposes. The left and right valves of M. arenaria are morphologically distinct (the left valve possesses a protruding tooth or chondrophore) and were therefore painted different colors. Each M. arenaria valve type (left, right) was consecutively numbered in groups of ten, with the lowest number on the largest valve and the highest number on the smallest valve. The largest and smallest valves, in each group of ten, were very nearly the same size. In this way, any differences in movement between either left and right valves, or large and small valves could be noted.

Identical experiments were conducted at each station. Twenty marked valves (10 right, 10 left) were placed at each station, within 15cm of the stake. The valves were orientated such that their long axes were arranged radially about the stake, with even numbered valves concave upward and odd numbered valves concave downward (photo No.1).

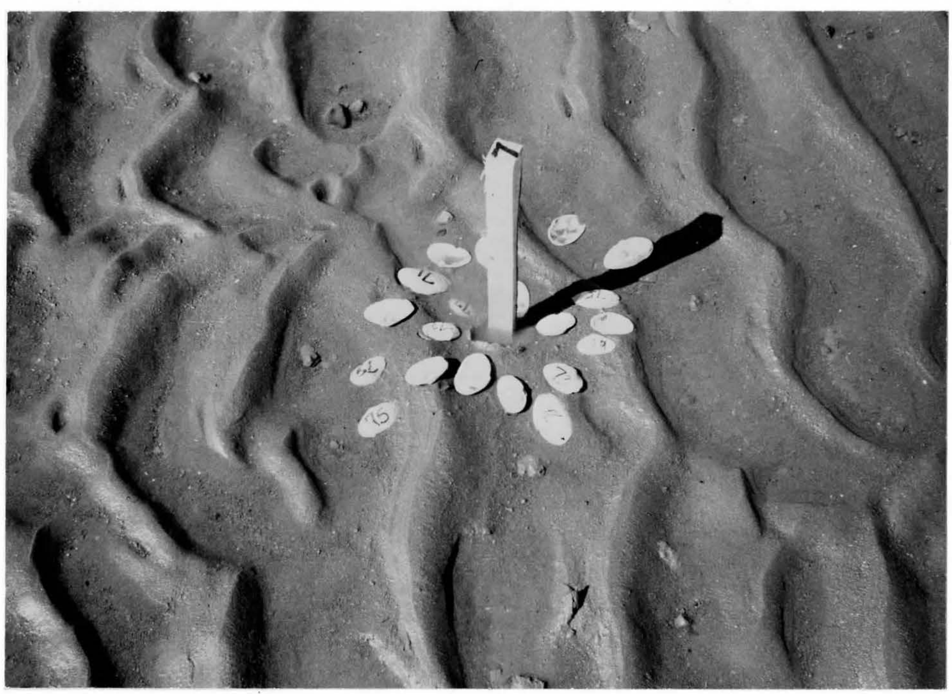


Photo #1 Arrangement of Mya arenaria valves at beginning of transport experiments.

Due to the opacity of the water, in the Minas Basin, it was possible to observe the experimental valves only at low tide. The measured transport values between successive low tides are therefore resultant movements only. The actual nature of valve movement must be inferred from these data.

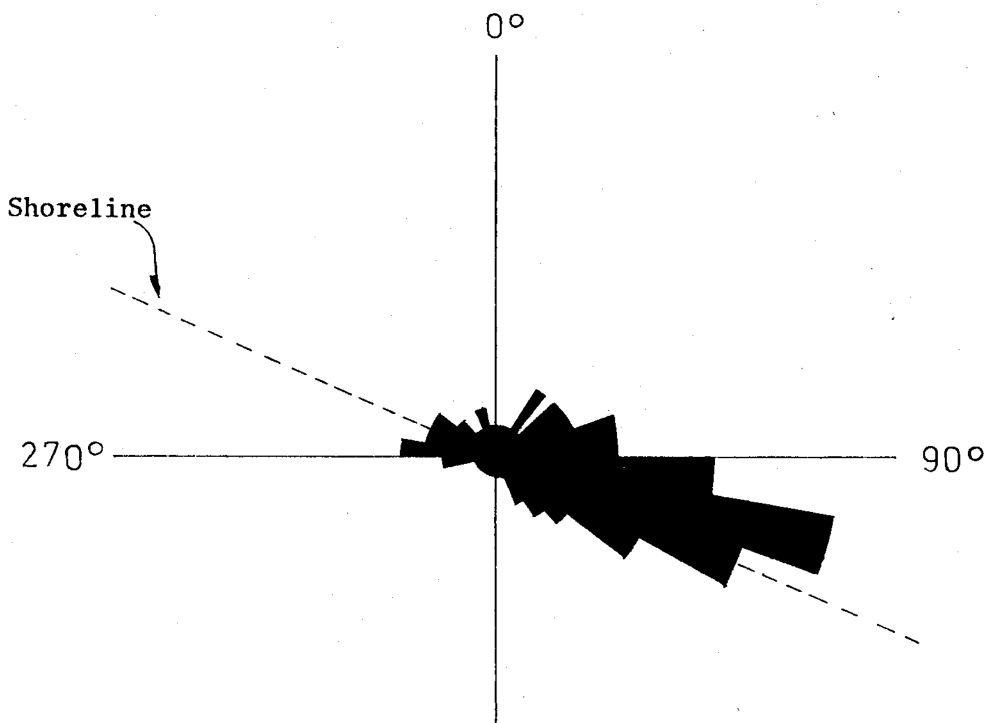
EXPERIMENTAL VALVE TRANSPORT-OBSERVATIONS

The simplest method of displaying valve movement (magnitude and azimuth) is by the use of 'Rose' diagrams. The number of observations recorded at each station is too low to warrant a station by station analysis. Therefore the observations are presented as grouped data (mud flats, sand flats, and cobble flats).

The data for Mya arenaria valves was analysed and is displayed in several rose diagrams:

1. Diagram #1 is a plot of frequency of movement/azimuth for all observations (St. #1 to #15). This indicates that shell movements are mainly toward the east (110^{o}).

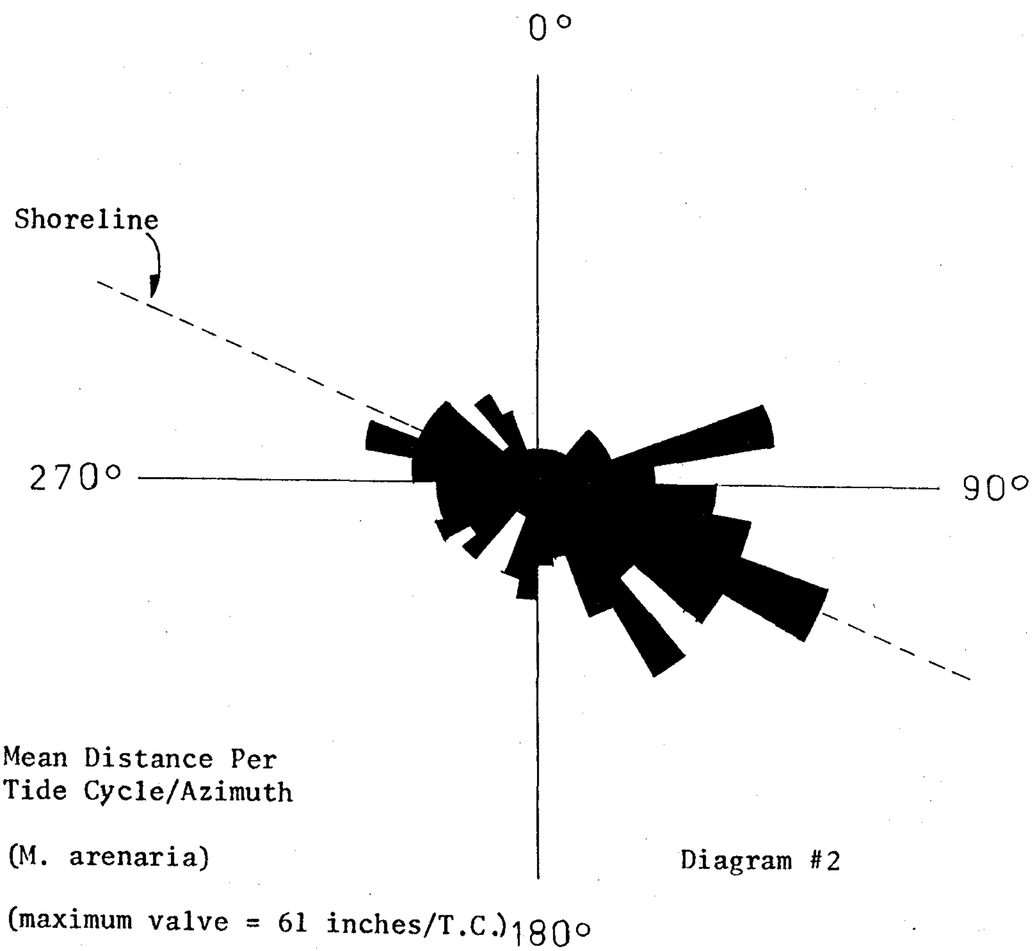
2. Diagram #2 indicates the average net distance of movement/ azimuth for these data.



FREQUENCY/AZIMUTH (Mya arenaria)

(maximum value = 70)
(total # plotted = 520)

Diagram #1



Mean Distance Per
Tide Cycle/Azimuth

(M. arenaria)

(maximum valve = 61 inches/T.C.)

Diagram #2

3. Diagram #3 presents the total distance/azimuth for all readings. This combines Diagram #1 and Diagram #2, and indicates the magnitude and direction of shell movement during the study period (5 days).

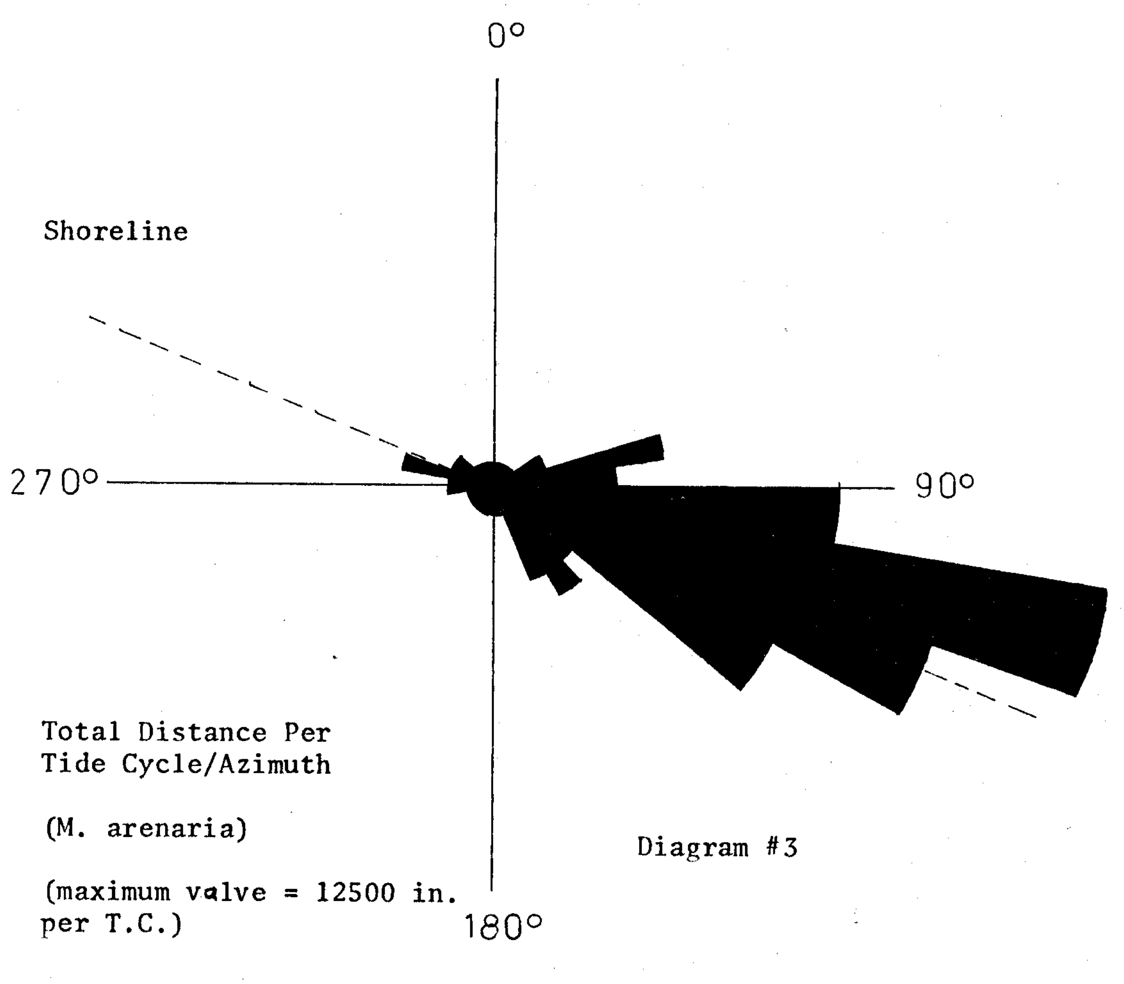
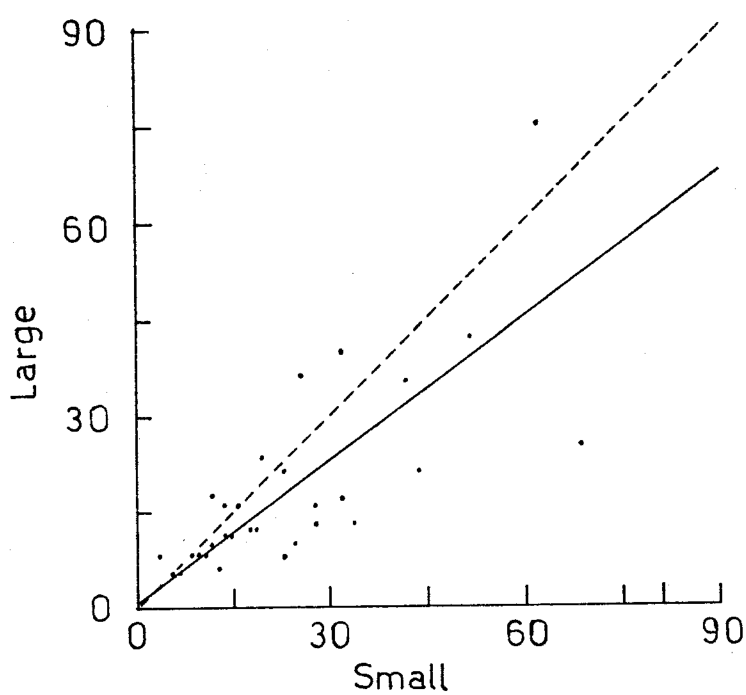


Diagram #3

4. Diagram #4 presents the data concerning the distance of movement relationship between large: small valves. Each point represents the mean values of large shell distance (valves #1 - #5) and the corresponding small shell distance (valves #6 - #10) for each observation, at each station. It should be noted that 8 points fall above the line:large shell distance = small shell distance, and 20 points fall below this line.

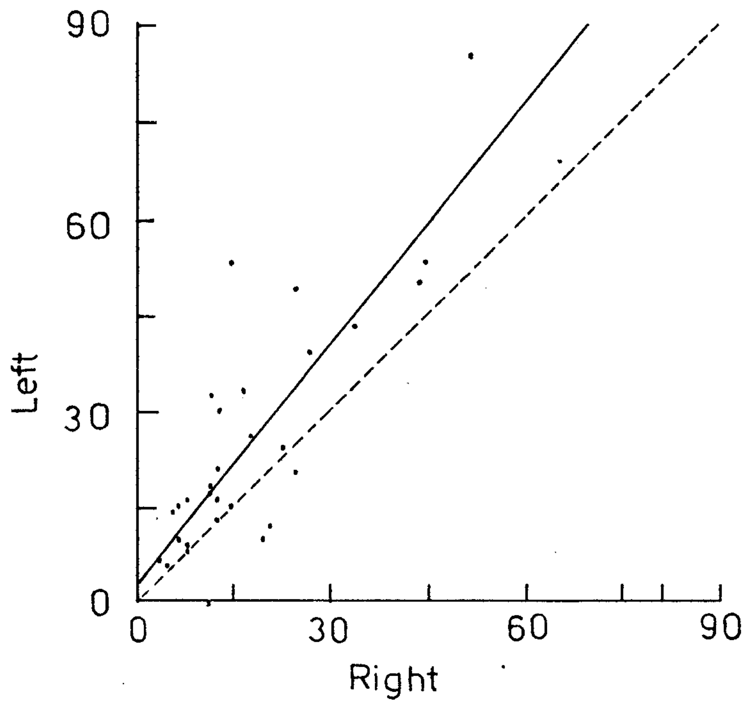
Diagram #4



Large shell movement/Small shell movement for Mya arenaria.
(inches/tide cycle)

5. Diagram #5 indicates the relationship between mean left valve distance of movement and the mean right valve distance of movement. Twenty three points fall above the line: left distance = right distance, and 4 points fall below this line.

Diagram #5



Left valve movement/Right valve movement for Mya arenaria
(inches/tide cycle)

INTERTIDAL CHANNELS-INTRODUCTION

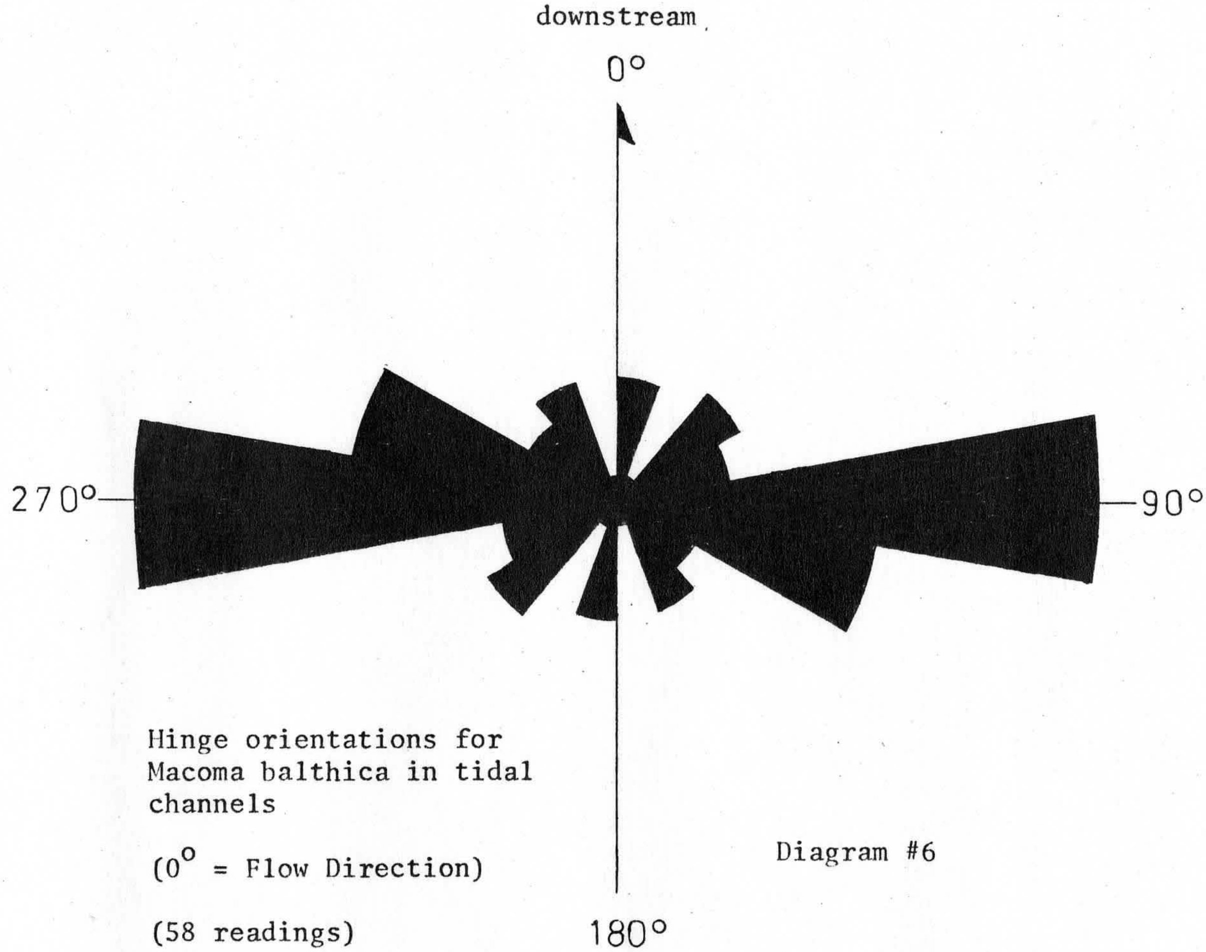
Several stations were established within intertidal channels. The purpose of the valve transport experiments at these stations was to determine the competence of intertidal channels to transport valves, and the amount of valve movement. These channels typically occur within the mudflats of the study area. Both Mya arenaria and Macoma balthica valves were used in these experiments. Observations of valve orientations within channels were recorded.

INTERTIDAL CHANNEL-OBSERVATIONS

It was observed that M. arenaria valves within small channels (1 m wide) were not transported. The valves commonly remained on the channel bottom, as they had been placed, for the duration of the study (5 days). These valves did not display a preferred orientation with respect to the channel current.

Macoma balthica valves (articulated and agape) were transported by channel currents. The average amount of movement was approximately 30 cm. downstream per day. Most of the natural valves appeared to display a preferred orientation with respect to the current direction (photo #2) Data concerning the orientation of empty Macoma balthica valves within intertidal channels is displayed in diagrams #6 and #7.

6. Diagram #6 presents a rose diagram of the orientation of natural articulated valves of M. balthica (agape) within channels. The orientations were determined by the azimuth of the hinge line. The 0^{o} azimuth of the diagram represents the direction of channel flow downstream.



Hinge orientations for Macoma balthica in tidal channels

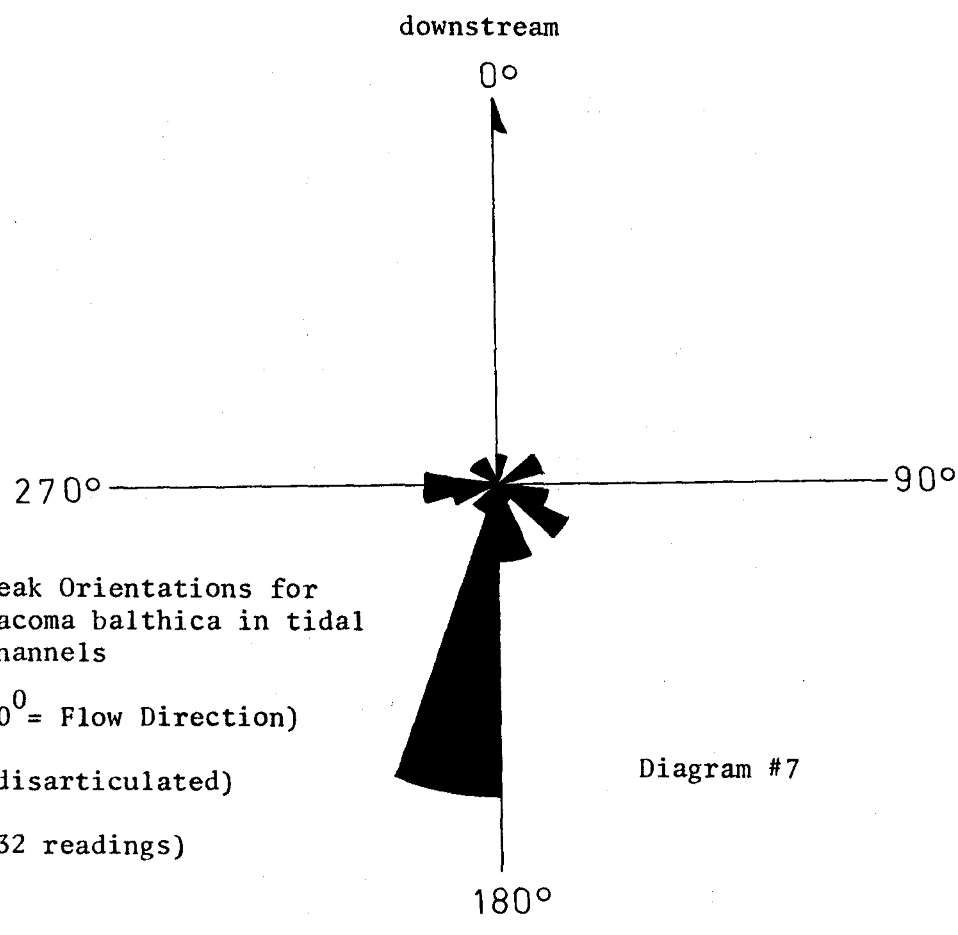
(0° = Flow Direction)

(58 readings)

Diagram #6

Photo #2 Macoma balthica valves oriented within a small intertidal channel.

7. Diagram #7 presents the orientation of disarticulated, and closed articulated valves of <u>Macoma</u> <u>balthica</u> within intertidal channels. The azimuths of the valve beaks, with respect to current direction, are plotted.



Beak Orientations for Macoma balthica in tidal channels

(0^0= Flow Direction)

(disarticulated)

(32 readings)

Diagram #7

SURFACE ORIENTATION OF VALVES-INTRODUCTION

Valves of Macoma balthica upon the sediment surface were observed and their orientations recorded (photo #3). Orientations of M. balthica valves were determined by the azimuth of the hinge line for articulated open valves and the azimuth of the beak for disarticulated or articulated closed valves. Valves of Mya arenaria are rare on the mud flats.

Photo #3 Macoma balthica valves orientated upon the mudflats. Disc is 40 cm. in diameter.

SURFACE ORIENTATION-OBSERVATIONS

Local adjacent groups of Macoma balthica valves were observed and their orientations recorded. M. balthica orientations on the mud flats are presented in diagrams #8 (a,b,c,).

8. Diagram #8 (a,b,c) presents the orientation of adjacent groups of M. balthica valves. The relative position of the samples is presented in Diagram #9(b).

9. Diagram #9 presents the orientation of M.balthica valves from an area toward the north-west of sample #8.

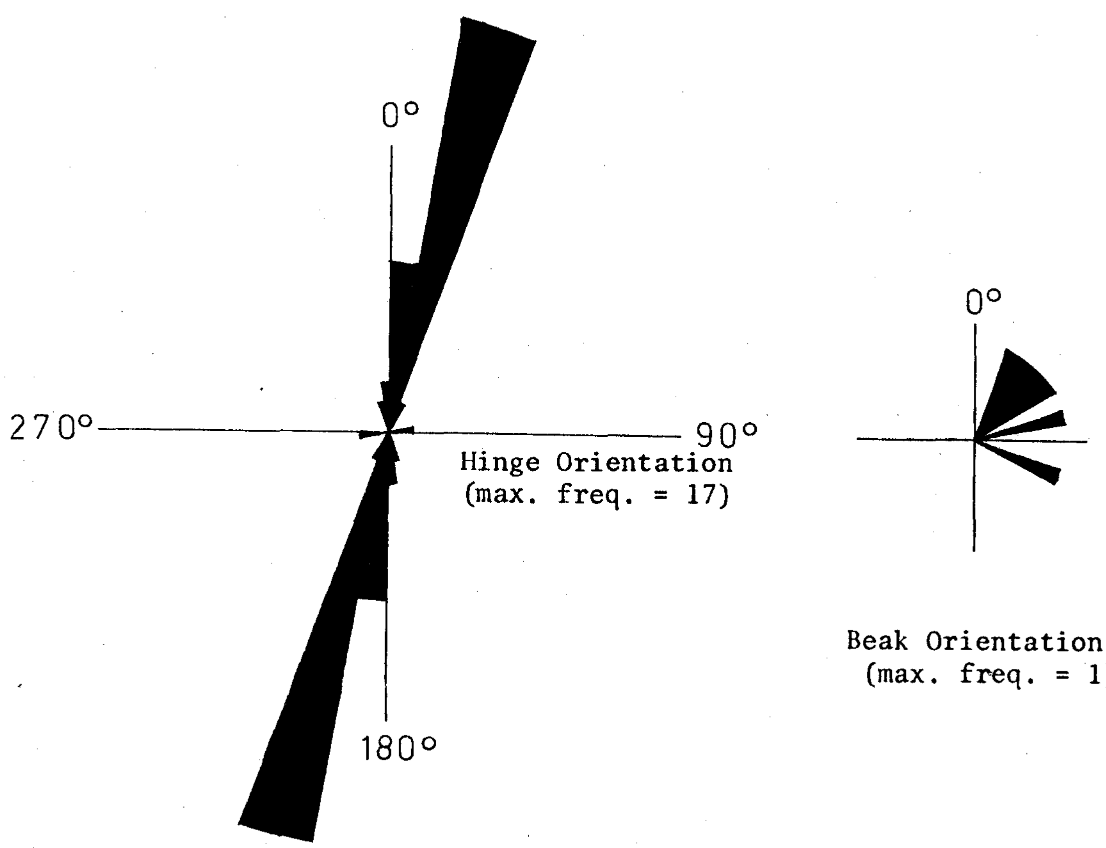


Diagram #8(a)

Surface orientation of Macoma balthica valves.

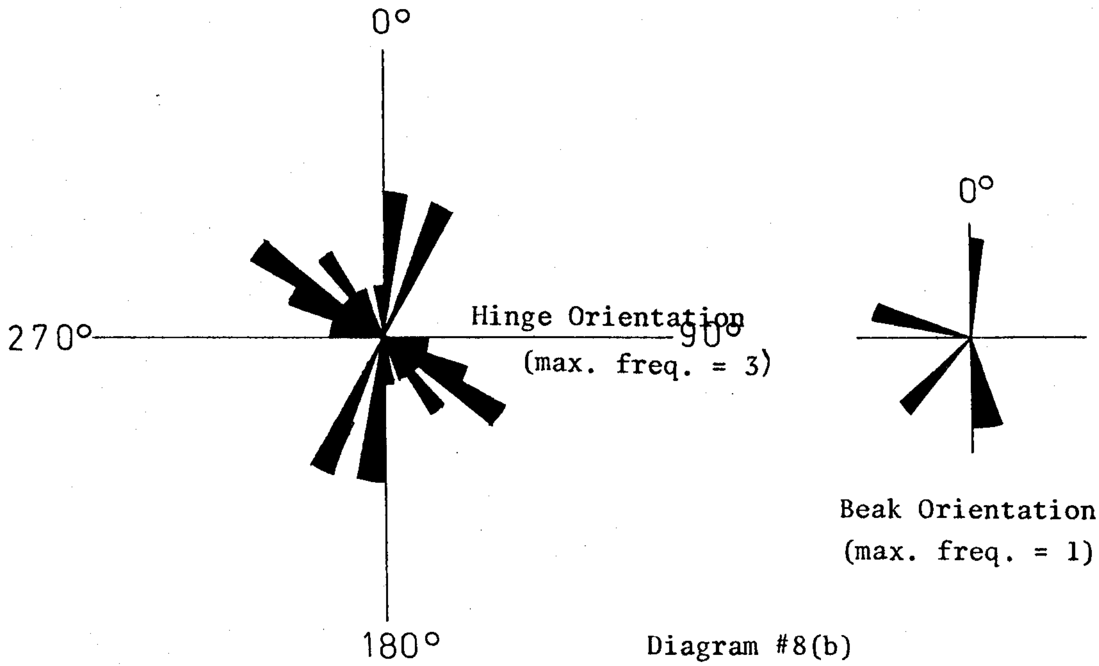


Diagram #8(b)

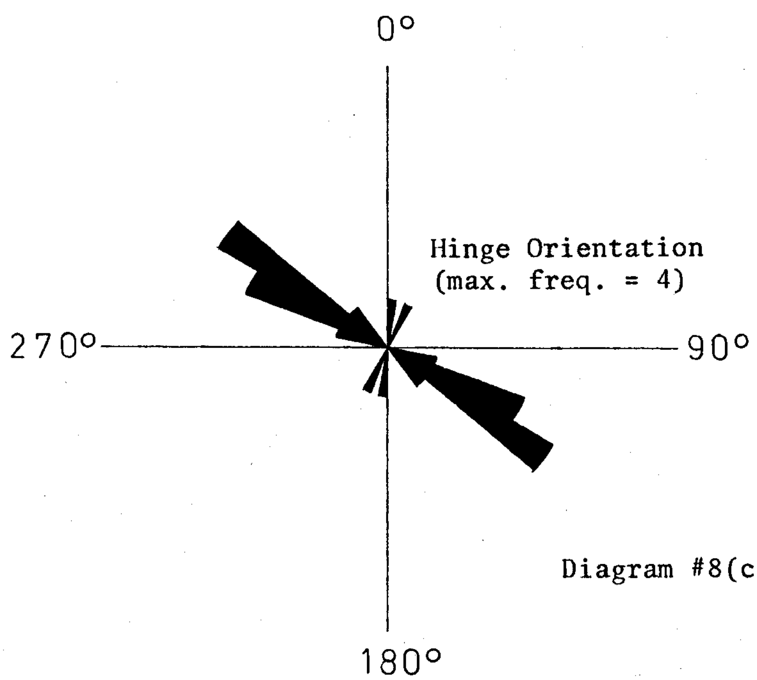
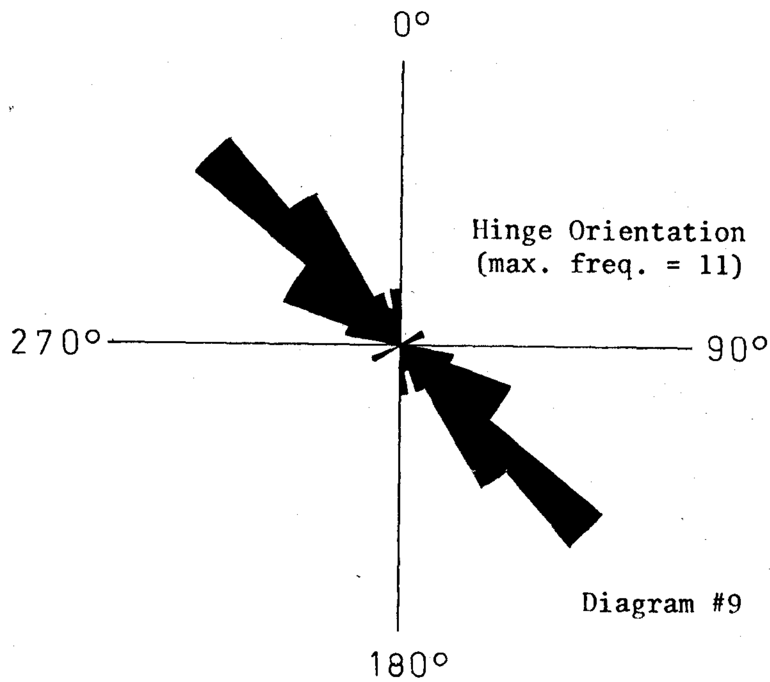


Diagram #8(c)

Surface orientation of Macoma balthica valves



(Station F-approximately 50 m. to 330^{o} from Area of Diagram #8)

FLUME EXPERIMENTS

A recycling flume was used to observe transport of Mya arenaria and Macoma balthica valves, when subjected to unidirectional currents of various velocities. The flume was approximately 5.5 m. long and 15 cm. wide. The bottom was covered with a mixture of coarse and fine sand (grain size distribution unknown). Experimental valves were place upon the sediment, and their amount of movement and orientation were noted a several time intervals. The valves of M. arenaria were orientated such that their beaks pointed 'upstream', before the experiment began.

FLUME OBSERVATIONS

The left and right valves of M. arenaria were observed to move approximately the same distance. At a current velocity of .5 m/sec. the rate of movement was approximately .2 m/hr.. These observed rates of transport contain considerable experimental error. Local scouring often brought the valves in contact with the smooth plexiglass surface of the bottom of the flume, aiding shell transport.

The orientation of M.arenaria valves within the flume is presented in Diagram #10 and Photo #4.

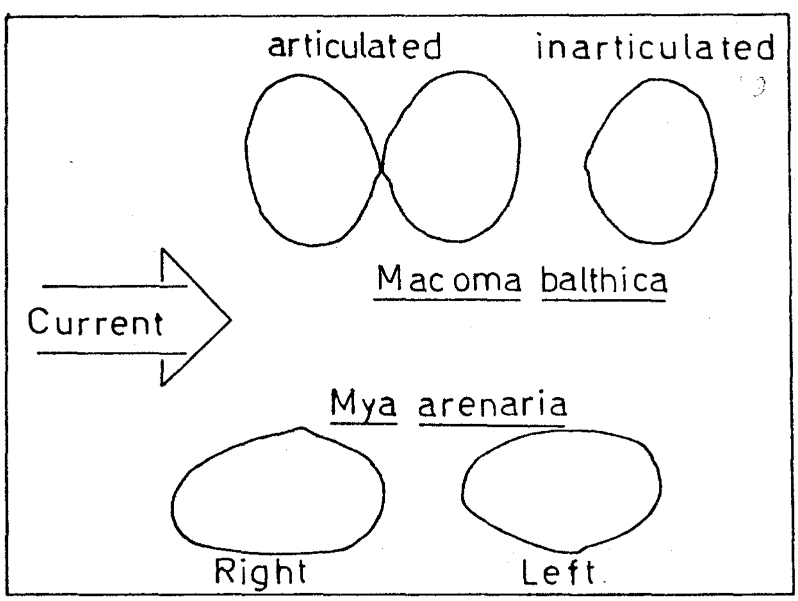


Diagram # 10

Orientation of Mya arenaria valves in the flume.

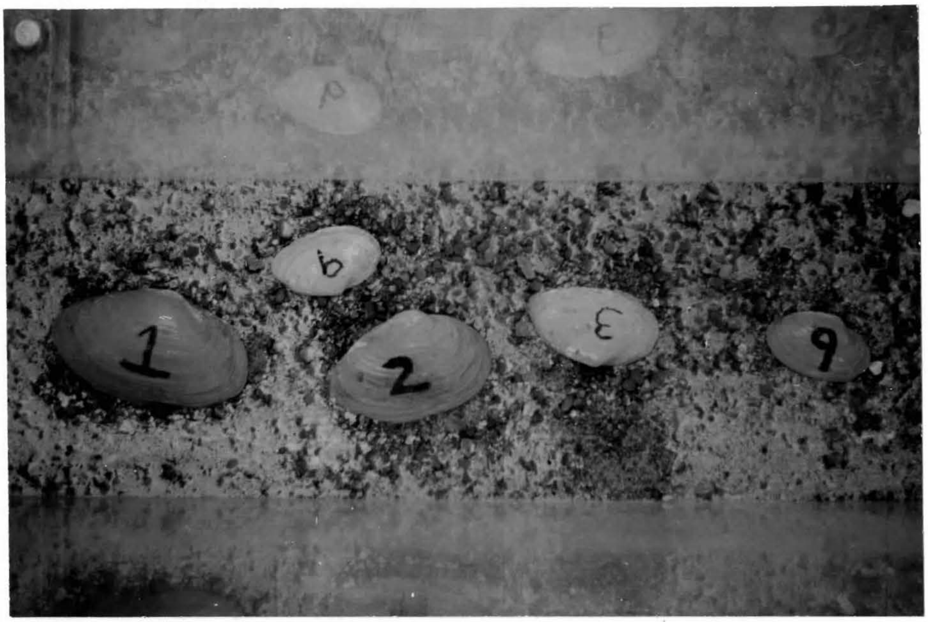


Photo #4

Mya arenaria valves orientated within the flume.

Current is from the left.

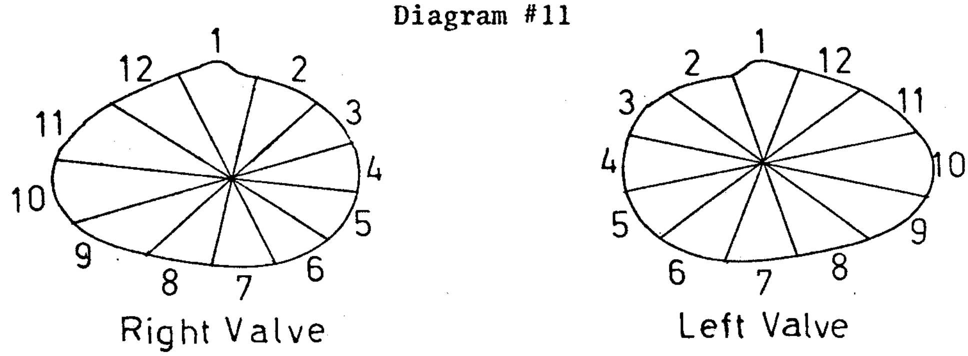
Of significance may be the observation of shells rising up to displace trapped air, as the flume was turned on. These valves commonly moved a short distance after 'bumping'.

PELECYPOD VALVE BREAKAGE

Broken valves of Mya arenaria were commonly observed upon the lower intertidal cobbleflats of the study area. This breakage is undoubtedly a result of valve transport. The degree of valve breakage must therefore be dependant upon valve strength and the magnitude and frequency of blows, to the valves, during transport. Valve transport experiments have already been conducted; what remains now is to determine the effect of transport on the mechanical destruction of valves.

Before the degree of shell breakage and the pattern of shell breakage can be thoroughly evaluated, it is necessary to establish a method of quantitatively describing these features. A quantitative measure of individual shell breakage was established by considering the amount of shell area missing from each valve. Areas of Right and Left Mya arenaria valves were numbered as in Diagram #11. Only whole valves and fragments which contained the hinge area were considered. This not only eliminated the use of both halves of a broken valve, but used the most resistant shell area as a guide (Schafer, 1972). These natural breakage data are further supported by experimental valve breakage in the laboratory.

Diagram #11

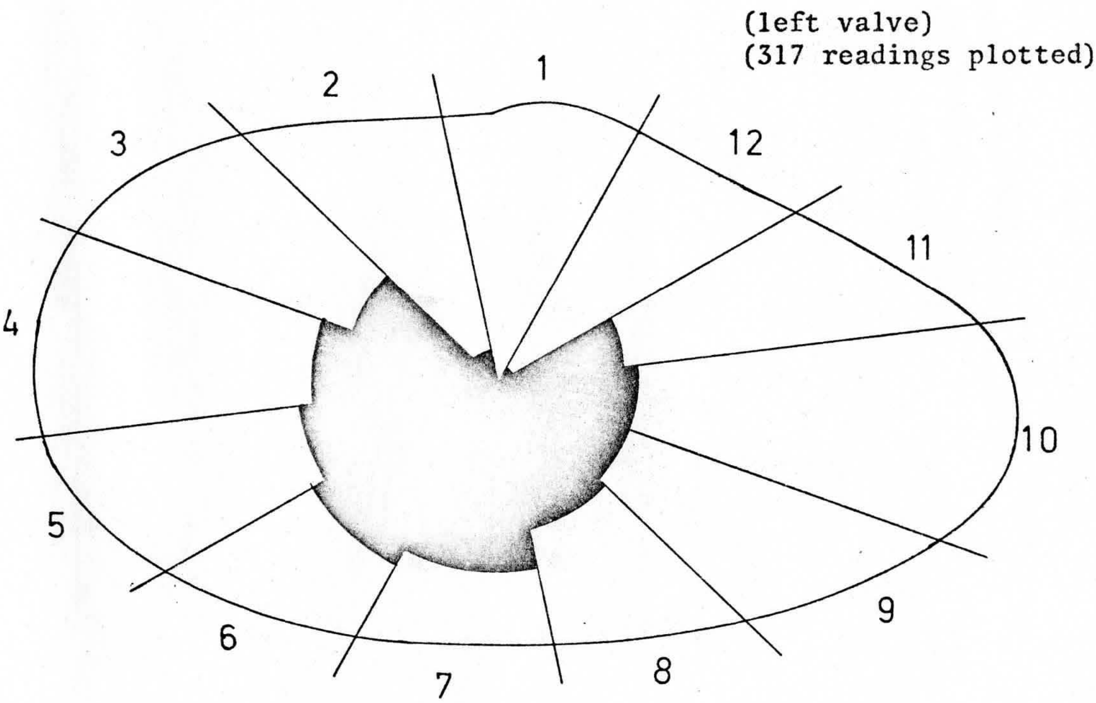


'Shell Areas' of Mya arenaria as defined by the author.

VALVE BREAKAGE-OBSERVATIONS

Breakage observations are presented in the form of valve rose diagrams:

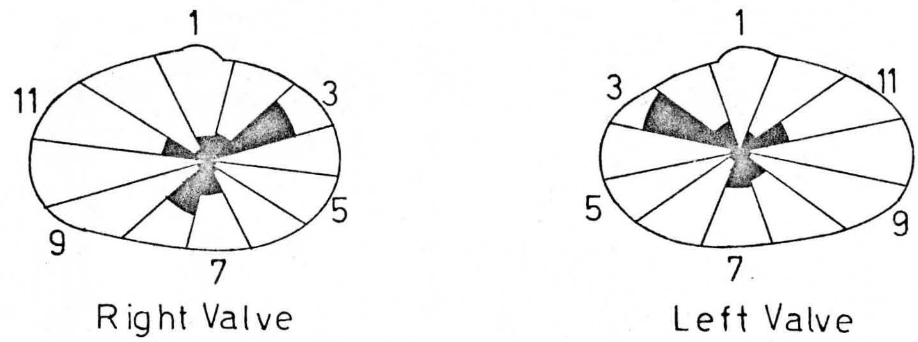
12. Diagram #12 presents the frequency of breakage with respect to valve areas. These data represent the breakage sustained by all collected valves.



Frequency of breakage/Shell Area for *Mya arenaria*.

Diagram #12

13. Diagram #13 indicates the frequency of breakage cracks with respect to shell area.



Frequency of breakage cracks/Shell Area for Mya arenaria.

14. Table #1 presents the relationship between magnitude of natural shell breakage and shell areas affected.

Laboratory studies of breakage of Mya arenaria valves were conducted, to determine the relative magnitude of a blow, to a given area, that would cause valve breakage. A unit blow, which was to approximate a shell striking a cobble, was simulated by dropping the shells from a height of 25 cm. onto a firm hard surface, in such a way that the initial area of contact could be readily determined. The breakage patterns produced were analysed to determine the relationship between, area of contact (receiving the blow) and the position of resultant valve breakage.

15. Table #2 indicates the experimental relationship between the magnitude of shell breakage and the shell areas affected.

16. Table #3 presents the experimental data concerning the area of contact and magnitude breakage.

TABLE # 2						EXPERIMENTAL BREAKAGE								BREAKAGE SEVERITY		NATURAL BREAKAGE												TABLE # 1
Shell Areas	1	2	3	4	5	6	7	8	9	10	11	12	%	# of areas	%	1	2	3	4	5	6	7	8	9	10	11	12	Shell Areas
	0	0	0	0	0	0	0	0	0	0	0	0	0%	1	20%	0	0	2	4	3	4	6	2	13	23	13	0	
	0	1	2	1	2	3	1	1	1	1	1	0	20%	2	10%	0	0	3	4	4	5	7	6	8	14	11	0	
	0	1	3	3	2	0	0	1	1	2	2	1	10%	3	10%	0	0	2	5	9	8	8	10	12	16	12	0	
	0	0	5	7	9	9	5	5	3	3	2	0	15%	4	10%	0	0	7	13	19	16	16	14	14	10	5	0	
	0	2	5	6	6	6	7	4	3	3	3	0	10%	5	5%	0	1	11	20	25	27	27	18	10	6	5	0	
	0	4	10	10	10	11	11	7	1	1	1	0	15%	6	10%	0	3	22	30	32	34	34	23	10	6	5	0	
	0	2	5	5	6	10	10	10	8	5	5	3	15%	7	10%	0	7	19	25	26	27	27	25	13	11	7	1	
	0	1	2	7	7	7	7	7	7	5	5	0	10%	8	5%	0	4	17	22	22	22	22	20	20	21	7	1	
	0	0	4	4	4	4	4	4	4	4	4	0	5 %	9	15%	0	3	45	48	48	48	48	48	48	48	45	3	
	0	1	1	1	1	1	1	1	1	1	1	0	1%	10+	1%	0	3	7	7	7	7	7	7	7	7	7	5	

TABLE # 3

AREA OF CONTACT	MAGNITUDE OF BREAKAGE
convex surface	high
concave surface	low
shell periphery	low

PELECYPOD VALVE DENSITIES

To determine the distribution of live and dead (empty) pelecypods, population densities were determined for several environments of the study area. Population densities were determined upon the sediment, within the sediment and within intertidal channels. Valve densities within mudflat and channel sediments were determined by taking 3 cores 20 cm. in diameter and 15 cm. long, per m^2. Cores were sieved and pelecypod valves counted. Surface densities were based on the counting of valves with a given area.

POPULATION DENSITY OBSERVATIONS

Table #4 presents the population densities of pelecypod valves within the mudflat sediment. To determine the population densities at depth(below 15 cm.) a hole 1 meter in diameter was dug near population #1 (photo #5). A few empty valves were found between 15 cm. and 20 cm. of the surface, but no valves were observed below 20 cm.. Some of the empty and live valves appeared to be blackened. No corroded valves or empty shell casts (ghosts) were observed.

TABLE # 4

	live	dead
population#1	24	3
population#2	66	2
population#3	154	18
TOTAL	244	23
average	81	8 (density/m^2)

Surface valve densities determined for the mudflat and cobble flat populations averaged 10 and 25 respectively. No live pelecypods were observed in the intertidal channel populations. The observed channel population densities are presented in Diagram #14. A general trend of increasing population density of empty Macoma balthica valves in a downstream direction should be evident.

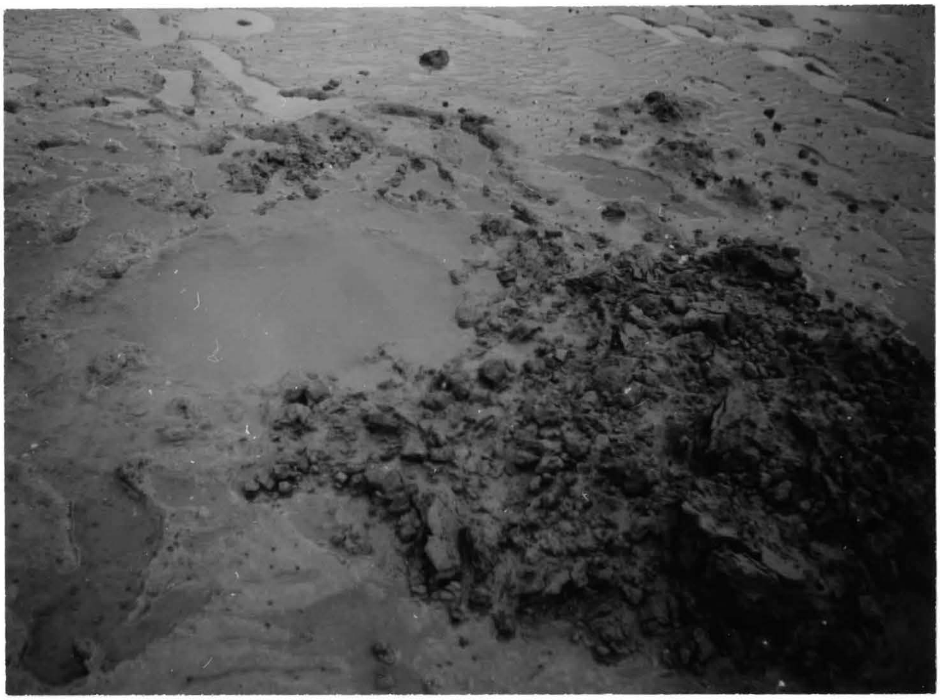
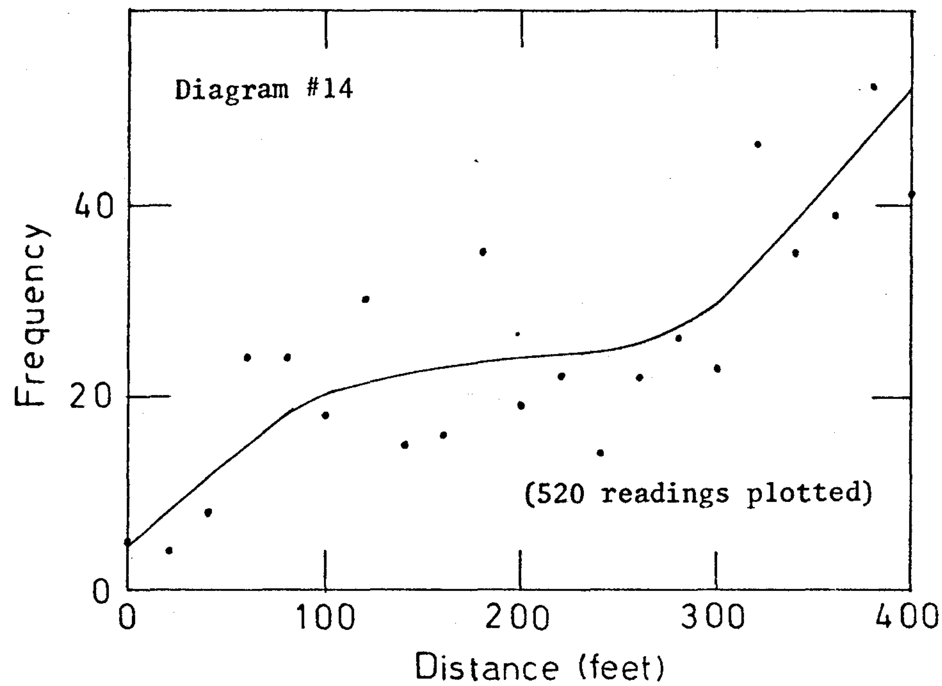


Photo #5
Hole dug to determine population densities at depth.

Note very poor sediment drainage, and footprint.

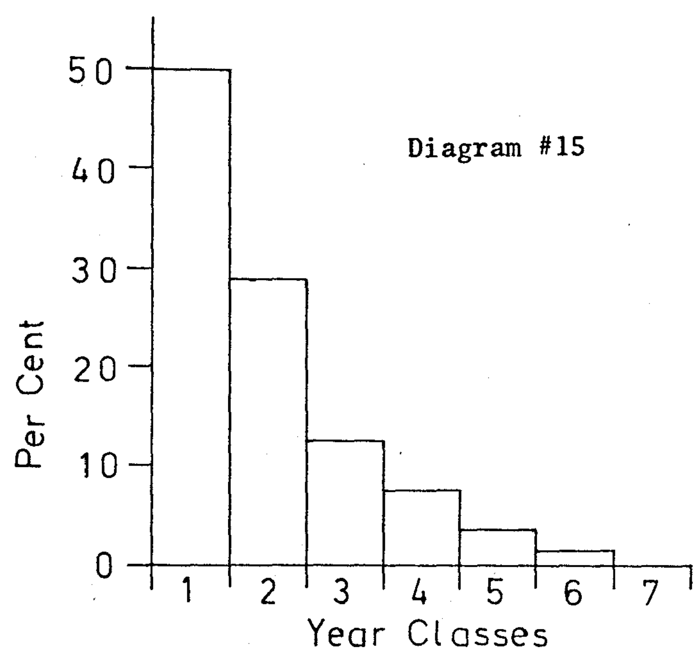


Density of Macoma balthica valves with intertidal channels.

DISCUSSION OF THE PROCESSES AFFECTING THE DISTRIBUTION OF THE PELECYPODS Mya arenaria AND Macoma balthica, IN THE STUDY AREA.

The pelecypods Macoma balthica and Mya arenaria live within most fine sediments of the Minas Basin. Macoma balthica commonly occurs in very fine sediments (muds) in densities of approximately $1200/m^2$. Densities in excess of $2500/m^2$ are not uncommon (Verena Tunnicliffe, personal communication). Mya arenaria prefers sandy sediments, where densities reach several hundred per square meter. With such high densities of live pelcypcds, many empty (dead) valves would be produced, and these would accumulate within the sediment.

The number of empty valves that would be expected to accumulate can be calculated by considering the density, age distribution, and death rate of the pelecypod population. Lammens (1967) presented the age distribution of several _Macoma balthica_ populations . A general model, based upon his finding, is presented in Diagram #15. If such a distribution is assumed to remain constant year after year, then the number of empty valves that would accumulate after a period of time can be predicted using Diagram #15. Thus the average population of _Macoma balthica_ (1200/m^2) can be expected to produce 570 empty valves/m^2 of sediment.



Age distribution of Macoma balthica
(After Lammens, page 323)

Population sampling within the study area indicated the average population density of Macoma balthica is approximately $800/m^2$. Such a population would produce 376 empty valves in one year, and 2250 empty valves in 6 years. The observed density of empty valves within the sediment was $80/m^2$, while the oldest members of the live population are at least 6 years old. It is therefore strongly suggested that mechanisms exist which remove these empty valves from the sediment.

Empty Macoma balthica valves could be removed by in situ dissolution, surface erosion, lateral intertidal channel migration, and possibly other mechanisms. The chemical stability of calcium carbonate pelecypod valves within various sediments is not well known(Krauskopf, 1967). The pore fluids of the upper few centimeters of most sediments are chemically similar to surface waters, and dissolution is not expected (Kahn,1932). In the study area and typically in many fine-grained intertidal sediments, a reducing zone exists below a few centimeters of the surface (Wetzel, 1937). Shell stability in this zone is unpredictable. It has been suggested that shells within this zone are not dissolved, but are hardened by the precipitation of iron-sulfide within the shell(Wetzel,1937). The lower sediments of the study area smelled of hydrogen-sulfide, and bluish-black valves were observed.

The chemical stability of pelecypod valves is determined by the eH and pH of the environment. Krauskopf (1967) indicated that accumulation of decaying organic matter would increase the acidity of deeper sediments, tending to dissolve pelecypod valves. The low eH values of such sediments suggest shell stability. Therefore predictions are hard to make. Corroded or empty valves ('ghosts') of Macona balthica were not observed in the study area. Field experiments in the study area, suggest that slight dissolution may take place within these lower sediments of the Minas Basin (Marika Karolyi, personal communication).

Valve transport is common in many marine environments. Before pelecypod valves can be transported by surface currents, they must be freed from their enclosing sediment. The scouring action of surface currents, and the lateral migration of intertidal channels are processes which can 'free' shells. Evidence of surface scouring was present in the study area. Rare local assemblages of dead (empty) Mya arenaria, in sandy areas, were observed in life position with half of their posterior above the sediment. Mudflats, which are occupied by Macoma balthica, are composed of very fine-grained sediments, and are typically more resistant to erosion. The mudflats are commonly areas of deposition, rather than sediment erosion. No such protruding assemblages, 'in life position', of Macoma balthica were observed. It is suggested that empty M. arenaria valves may be removed from sandy sediments, but empty valves of M. balthica remain in fine sediments.

Laterally migrating intertidal channels may be significant in the erosion, transport and deposition of large volumes of intertidal sediments (Van Straaten,1961, Schafer,1972). As channels migrate, much sediment is eroded together with its contained assemblages of live and dead (empty) pelecypods. The coarser sediments and pelecypod valves accumulate in the channel bottom as a channel lag deposit. Much of the eroded sediment is deposited further downstream. These processes, which are presented diagramatically in Diagram #16 (a), are explained by Van Straaten(1961) and Schafer (1972).

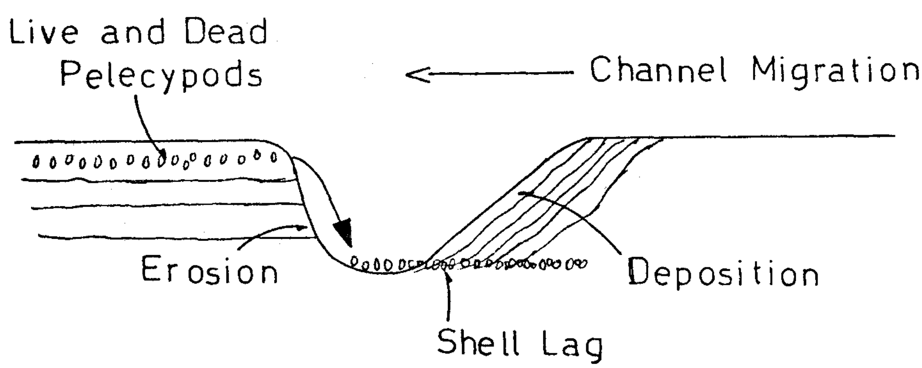
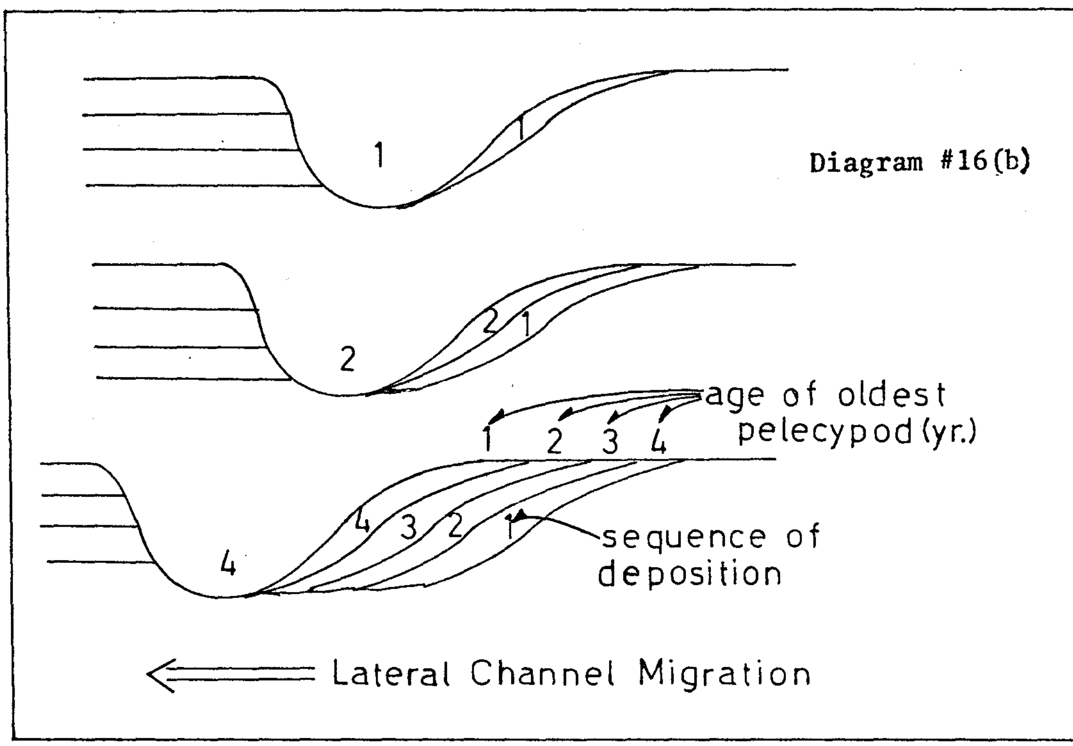


Diagram #16(a)

Migrating Intertidal Channels.

This model is only applicable in areas with significant lateral migration of channels. It is a relatively simple model, and has some interesting implications concerning the density and distribution of both live and dead (empty) pelecypod populations.



Migrating Intertidal Channels.

IMPLICATIONS OF CHANNEL MIGRATION

The accumulation of pelecypod valves within the channel lag is a very efficient method for removing pelecypods from the upper sediments. As erosion occurs in some areas, deposition of 'fresh' shell free sediment takes place in other areas. Juvenile pelecypods could now settle onto this fresh sediment and once again establish a living population. By the time of next spat fall, a year later, more fresh sediment would have been deposited and available for colonization. The first fresh area would also receive juveniles. In this way the age structure of the local population would slowly build up. This processes is presented in Diagram #16(b).

This model suggests that, if other processes such as dissolution, and surface scouring are not active, the number of empty valves can be correlated to the 'age' of the live population. This is not the case in the study area. The average density of live individuals was $800/m^2$, with the oldest members being at least 6 years old. The expected density of empty valves should be at least $2250/m^2$. The observed density was only $80/m^2$. Another factor which further adds to this discrepancy is the fact that channel migration rates in the study area are very low. Air photographs indicate no migration for the last several years, and only possible migration of less than 5 m. in the last ten years. No channels are present within 25 m. of the sample locations; a migrating channel has not disturbed the area for a long time.

If the effects of dissolution and surface scouring are assumed to be minimal, and if small intertidal channels, which are not resolvable on air photographs, are considered insignificant, then few explainations are available. The pelecypod valves must somehow move to the sediment surface, and be removed. This process will be called the "Escape Hypothesis".

THE "ESCAPE HYPOTHESIS"

It is known that upon the mudfalts, valve movement in an easterly direction parellel to the shore. The average rate of movement is approximately 2m/day. If it is assumed that valves are not carried in suspension but trapped by any depression, such as a footprint or intertidal channel as observed in the study area, and that lateral valve movement near the beach is insignificant, as was observed in the field, then it may be concluded that any pelecypod valves appearing on the surface of an interchannel area must have originated from the sediment of that area. As shell transport is significant in only an easterly direction, in several days the interchannel area should be swept free of all surface valves. These valves would accumulate in an intervening channel.

Within the study area, it was observed that a given interchannel area may be void of surface valves one day, but contain many valves the next day. Therefore some 'escape' mechanism(s) must exist to bring Macoma balthica valves to the surface. Several mechanisms may be suggested. These are tabulated in Table #5.

No likely mechanism of empty valve escape exists. Shell escape to the sediment surface, however, is strongly suggested.

MECHANISM	POSSIBLE EVIDENCE	EVIDENCE OBSERVED
birds	crushed valves	none
crabs	crushed valves	none
fish	feeding holes	none
gastropods	bored valves	many, but active within sediment
<u>Corophium</u>	burrows	very many
<u>Macoma balthica</u>	burrows	many

SURFACE PROCESSES AFFECTING PELECYPOD VALVES

Several forces may act to decrease apparent valve densities on the sediment surface. Pelecypod valves may be transported out of the study area, weakened by boring thallophytes, destroyed during transport or deposited in channel lags.

Surface shells, and possibly buried shells, are weakened by boring organisms: "Many investigators consider the calcium-carbonate-boring thallophytes as the most important destroyers of empty, marine mollusc shells" (Pia, 1937- from Schafer,1972, page). This type of shell weakening is probably quite important in the study area. Photograph #6 presents the common appearance of thallophyte-bored Mya arenaria valves from the cobble flats of the study area. Such weakened valves would be most susceptible to abrasion and breakage during transport.

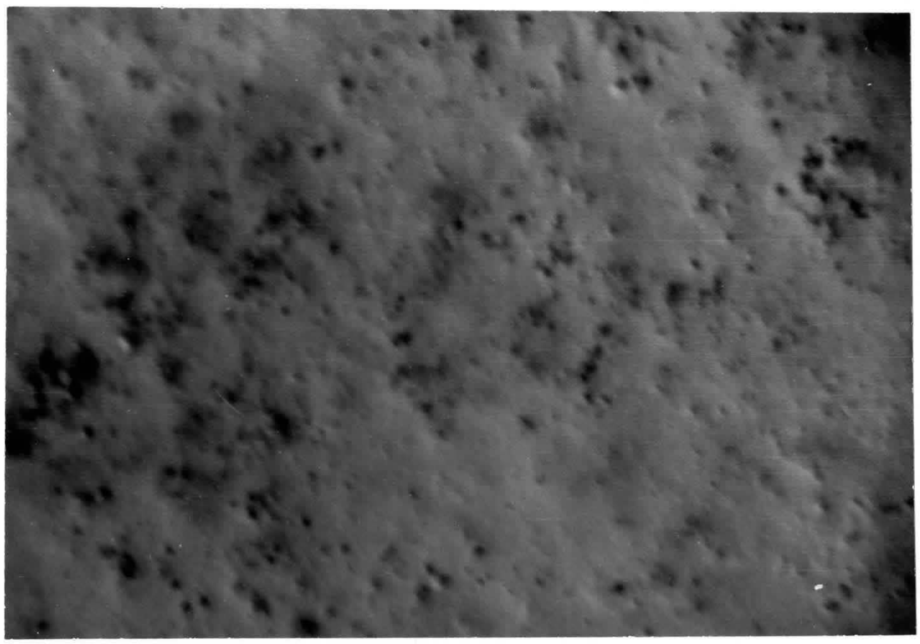


Photo #6
The appearance of thallophyte bored valves of Mya arenaria.

Mya arenaria valves rarely occur in the upper intertidal mudflats or within the upper intertidal channels. The rare occurence of Mya arenaria valves, and valves of the boring clam Zyrphaea, are undoubtedly due to ice rafting as there are no living populations with several hundred meters, and no occurences to the west of this area (behind gravel spit). The common occurence of large cobbles which rest upon the mudflats, must also be ice rafted relics.

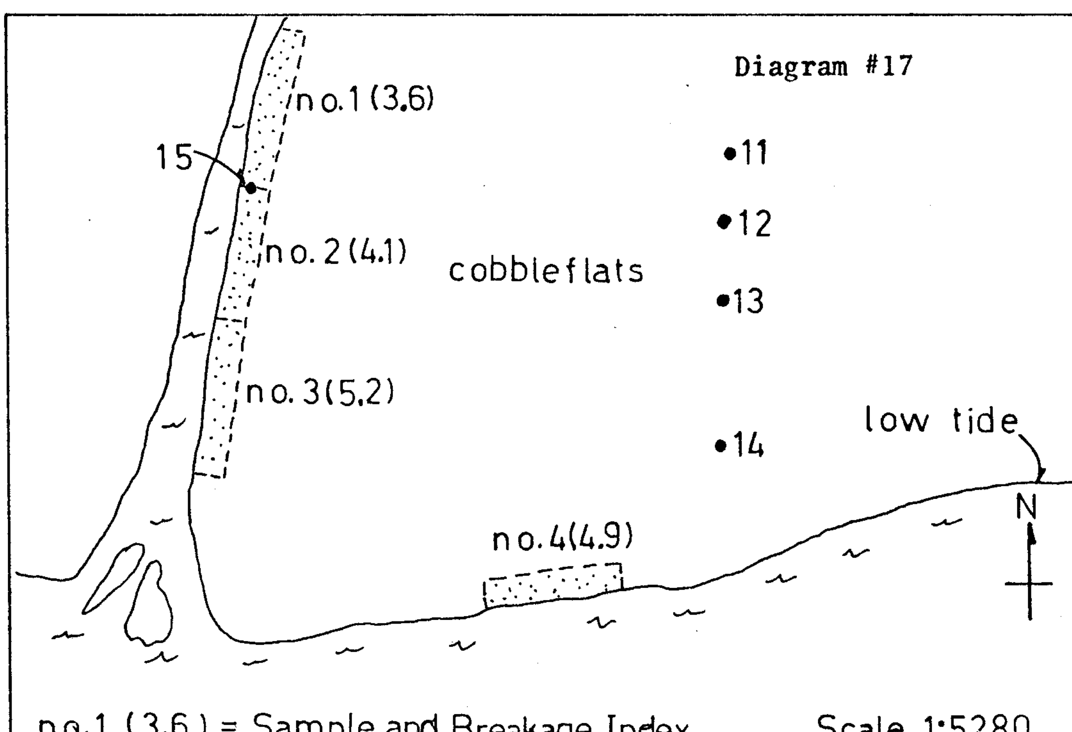
Mya arenaria valves are quite abundant beside the main intertidal channel and upon the lower intertidal cobble flats. The valves in this later area are rarely articulated, and commonly are broken to various degrees. The incidence of breakage within the study area varies from insignificant in the mudflats to very significant in the cobble flats. This is directly related to the nature of the substrates and the strength of tidal currents in these areas.

Shell destruction has been noted by several authors (Driscoll, 1967, Schafer, 1972). Schafer (1972, page 159) stated: "Valves are more frequently broken by impact than destroyed by faceting" or abrasion. "The fracture edges are irregular, but weak zones in the shell structure often determine where it breaks". As shell breakage is quite common in the lower intertidal area, a study was performed to investigate the significance of shell breakage to valve destruction. The relative amount of breakage might then be correlated to the relative distance of transport, by the collection and study of naturally occurring valves (and fragments) from selected sample sites.

Once a quantitative measure of individual valve breakage was established (see breakage experiments), a sample breakage index was defined as:

$$\text{Sample Breakage Index} = \frac{\Sigma\text{Individual degrees of breakage}}{\Sigma\text{of valves in the sample}}$$

The use of this index to correlate shell breakage to distance of transport met with moderate success. The sample locations and their corresponding Breakage Index are illustrated in Diagram #17. It should be noted that the breakage index increases downstream along the main channel. The slight decrease in the breakage index of sample #4 may be related to mixing with other valves from the west side of the main channel. (The channel disappears into a broad sheet flow zone below sample #4). In general, the position and breakage index of each sample is related to the relative distance of transport and the length of time spent with the high energy cobble flat environment. The breakage index may therefore be a good **valves** source area indicator.



Breakage Indexs along an Intertidal channel.

The genetic significance of this breakage index must be considered in light of the probability of contact and the resistance to breakage of various shell area. The relative strength of various shell areas may be indicated by the total number of times the areas are broken. Diagram #12 displays the required data.

If it is assumed that during transport, the shells have an equal opportunity of striking a cobble with any peripheral part of their shell, then the breakage pattern displayed in Diagram #12 must be related to local shell strength. The resistance to breakage of a given shell area is related to its thickness and curvature. A generalized shell thickness map is presented in Diagram #18, and a generalized shell curvature map in Diagram #19. By considering both these 'maps', it should be evident that high values of strength are indicated in the hinge area. The valve is thinner in the center than in the dorsal, posterior or anterior regions. In the area of posterior adductor muscle, the shell is commonly very thin. Shell breakage would be expected to occur along lines of shell weakness. The thinness in the antero-dorsal, postero-dorsal and mid-ventral shell regions, combined with general central weakness, indicates that breakage should be expected along lines joining these three areas. These correspond approximately to shell areas 3,11 and 7 respectively. If the assumptions of shell strength and weakness are correct, they will be supported by natural valve breakage patterns. The hypothesis can be tested by determining the frequency with which major breaks or cracks occur in each of the 12 shell areas. These data are displayed in Diagram #13.

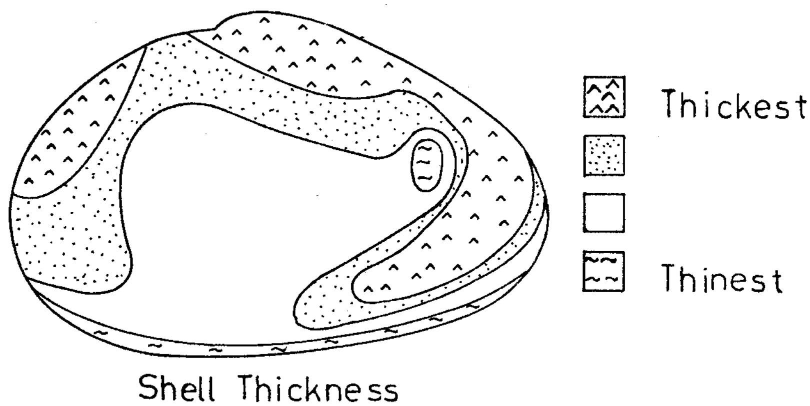


Diagram #18

Generalized Shell Thickness Map for Mya arenaria

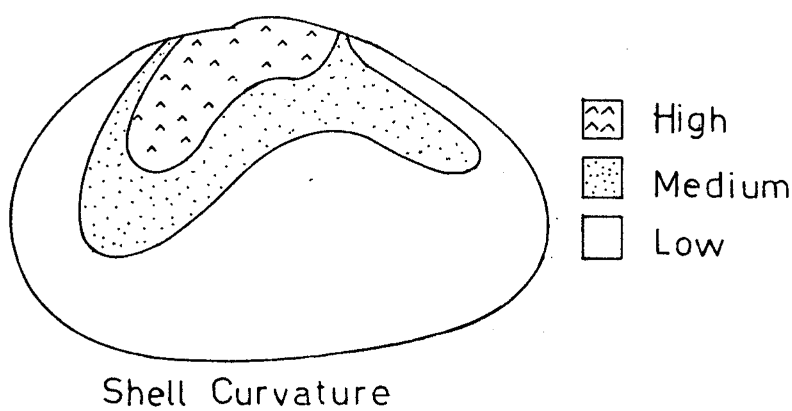


Diagram #19

Generalized Shell Curvature Map for Mya arenaria.

By examining Diagram #13, it is apparent that crack frequencies of Left valves are most significant in areas 2-3, 7-8, and 11. Significant crack frequencies in Right valves occur in areas 1-3, 7-8, and 11. The only major dissimilarities between the crack area/ frequency distribution of Left and Right valves, occur in shell areas number 1 and 12. The right valve of M. arenaria is much more often cracked through the hinge than is the left valve, while the left valve is more often cracked through area #12. These discrepencies might be due to the strengthening of the Left valve hinge area by the chondrophore

The breakage pattern of Mya arenaria valves was also qualitatively described by Schafer (1972). He states, on page 159,- "of the left valve of Mya arenaria only the hinge and chondrophore remain, and the hinge of the right valve frequently breaks crosswise." Breakage from area 3 to area 11 is required for the hinge and chondrophore to remain. Little significant crack or breakage frequency variation between the Left and Right valves, is evident at areas 3 and 11. If adjacent areas are included in the relative Left-Right crack frequencies, a significant difference is evident, as was suggested by Schafer. Cracking through the hinge of the right valve, is also seen to be much more frequent than in the left valve. Schafer also stated, that Mya arenaria breaks along the growth lines; such significant growth line breakage is not indicated by this author's natural samples, in which only 10% of the valves (often corroded) contained minor breakage of this type. Breakage across growth lines is far more common.

By comparing the probable positions of shell weakness with actual areas along which breaks typically occur, it can be ascertained that shell breakage patterns are a direct function of shell/strength and thickness. It is still not known what magnitude of blow is required to cause shell breakage, and what magnitude of break will occur. A comparison of magnitude of shell break and shell area affected, may give an indication.

These Tables show that the magnitude of shell breakage is highly dependant upon the area broken. For example, the simplest break, as defined by the author, occurs with the greatest frequency in area 10, and also with significant frequency in adjacent areas, 9 and 11. If the probability of each shell area striking a cobble during transport is considered equal, then the high frequency of minor breaks in areas 9 to 11 suggests this area is relatively resistant to major breakage. This suggestion is further supported by the low frequency of involvement of this area (9-11) in major breakage (over 5 areas broken off). Areas 4-8 display the reverse frequency/breakage severity relationship. These are (4-8) seldom display minor breakage, but have the highest frequency of involvement in major breakages. It may be postulated that a blow of unit force to areas 9-11 would produce minor breakage, but the same blow to areas 4-8 would result in severe breakage. This is indicated by the "migration" of breakage loci, as the severity of breakage increases.

To test this hypothesis, and determine the relative magnitude and repetition of blows required to cause breakage of one or more areas, *Mya arenaria* valves were subjected to breakage experiments in the laboratory.

The first experimental observation was that *M. arenaria* valves are very resistant to breakage if struck in the peripheral areas. However, shells which received blows to the convex surface often not only broke, but shattered into several pieces. Breakage often occurred upon the first blow, but commonly several blows were required to achieve shell breakage. An unexpected observation, was that smaller thinner shells were often more resistant to breakage. Probably the most signigicant observation was that a uniform blow produced a wide variation in the severity of breakage. A unit blow to the convex surface could result in the break of from 1 to 10 areas. Thus the proposed valve "Breakage Index" is not a good predictor of unit blows received by a "broken" population. The "Break Index" is not based on the gentic considerations of shell breakage.

The experimental shell breakage results are tabulated in Table 1 and 2. It should be remembered, when comparing or contrasting the two breakage patterns, that the experimental breakage was produced by single blows to the convex valve surface, while the natural breakage is a mature assemblage (possibly broken several times) and includes blows to all shell regions. Table #2 clearly indicates that a single uniform blow to the convex surface can produce a wide range of breakage severity. A comparison of both natural and experimental breakage indicates that patterns are basically similar, although discrepancies exist. The experimental breakage shows no unit breaks, no "migration" of breakage loci, and a paucity of severe breakage (9 areas broken). These discrepancies are undoubtedly due to the dissimilarities in types of breaking blows. Obviously all shells are not broken by blows to the convex surface in the natural environment. Other methods of breakage must exist, such as the one(s) responsible for the frequency of unit breaks in natural assemblages. Shells must undoubtedly be broken by blows to the shell periphery, and by bending of shells wedged between cobbles. Probable causes of shell breakage are indicated in diagram #20. The common causes of shell breakage can be readily ascertained from this table. It is evident, by considering probability of contact and the resistance to breakage due to contact at various shell areas, that a blow to the convex valve surface are probably most significant causes of shell breakage. Breakage due to contact along the valve periphery was difficult to achieve. Contact at the beak often resulted in a dorsal-verntral break through the hinge, or the breakage of a small area including the beak, approximately along growth lines. Contact to the peripheral verntral, anterior and posterior valve regions very seldom produced shell breakage. A natural breakage pattern, which was difficult to explain, was a hole in the middle of the shell. It was initially thought to be breakage around a gastropod borehole. This breakage pattern was never produced by blows to the convex surface. However, the experimental evidence seems to indicate a punched out hole is the typical breakage pattern produced by a blow to the concave surface. Such a hole was produced experimentally eleven times in a row. The breakage of shells due to wedging between cobble is not known for certain, but wedged shells commonly occur in the field.

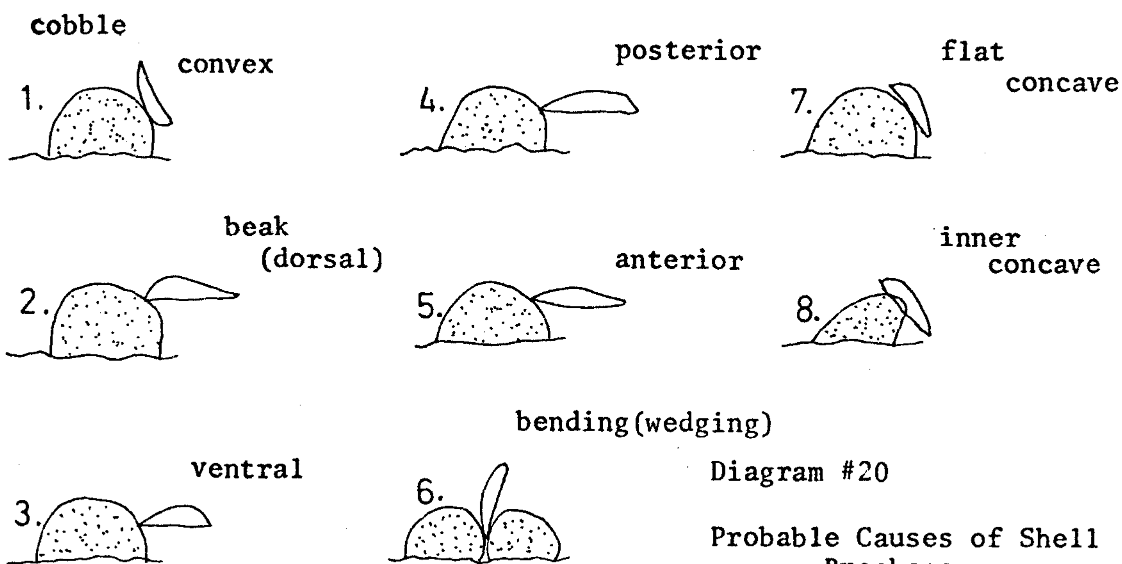


Diagram #20

Probable Causes of Shell Breakage:

TABLE no.

Type of Contact	Probability of Contact	Relative Resistance to Breakage	No. of Blows to Break	Area where Cracks occur
1	High	Very Low	2	7,3,11
2	Medium	Medium	5	1,7
3	Medium	Very High	15	?
4	Medium	Very High	20+	?
5	Medium	Very High	20+	?
6	Medium	Very High	20+	?
7	High	High	15	?
8	Very Low	Low	5	center punched out

PELECYPOD VALVE TRANSPORT AND ORIENTATION

Pelecypod valves within intertidal areas are transported by the currents of intertidal channels, and the currents of the flood and ebb tides. Current velocities within channels are usually less than .5m/sec. while tidal current velocities are commonly between 1 and 2m/sec (Klein, 19). On several occasions, the flood tide current was observed moving in an easterly direction near low tide. Tell-tales or sand deposits in the lee of cobbles occur in the study area (Photo #7). These indicate ebb tide current directions toward the west, at approximately 260^{o} azimuth. Therefore the flood and ebb tides flow in approximately opposite directions.

Valve transport, as observed at low tide, is directly related to the relative influences of flood and ebb currents. The greater velocity of the flood tide is indicated in Diagram #3, by general valve drift in an easterly direction. Because of the alternating influence of the flood and ebb tides, valves display a 'back and forth' motion. Therefore the actual distance of movement is several times greater than the average rates indicated in Diagram #2. The average distance of valve transport on the cobble flats during one tide cycle may be 10 meters or more (back and forth).

The mud flats, unlike the cobble flats, contain many intertidal channels. If eastward drifting valves encounter such a channel, they will become trapped and accumulate as part of the channel lag. Valve transport within intertidal channels is much slower than on the flats. The average rate is approximately 30cm/day. Channel flow is virtually

Photo #7(a,b)

Tell-Tale formed by ebb tide current (260°)

unidirectional, as tidal currents seldom effect the channel bottoms. However, if the channel lies in an east-west direction, the effects of tidal currents may be significant. Station #6 is situated in such a channel (photo #8). It is interesting to note that although channel flow is in a westerly direction for approximately 14 hours a day, at low tide, the valves drifted eastward in an upstream direction.

Valves within channels often show a marked preferential orientation with respect to current direction. Diagram #6 and #7 indicates the orientation of empty Macoma balthica valves within small intertidal channels. Valves upon the mud flats commonly show local preferential orientation. Such adjacent local groups of M. balthica valves are presented in Diagram #8 (a,b,c). From the gradual change in preferred orientation, it may be concluded that the orientation of any local group of valves on the sediment surface, represents only the direction of the last current strong enough to orient the valves. Therefore it is suggested that intertidal current directions, obtained from pelecypod valve orientation, be considered in light of this evidence.

The orientation of Mya arenaria valves on the cobble flats is not good, and may be related to the nature of the substrate. Nagle (1967, page 1124) stated: "Shells may become entangled on projections on gravel..., thus developing nondiagnostic orientation." As the cobble flats are representative of such an environment, poor orientations are to be expected. Nonetheless, the valves were generally orientated such that their anteriors pointed in the direction of ebb tide flow (to the west), as indicated by tell-tales.

Photo #8

Shallow intertidal channel with flow toward the west but shell movement to the east (station #6).

The flume experiments confirmed these preferred orientations. The unidirectional current of the flume, with a velocity of .5m/sec., quickly orientated most of the Mya arenaria valves to this anterior downstream position. The orientations of empty Macoma balthica valves in the flume were also identical to those observed in the small intertidal channels (Diagram #6, #7, and #13).

It is well documented in the literature that morphologically distinct valves (right-left, large-small) may be sorted by currents and waves. Diagrams #4 and #5 indicate that small valves and left valves appear to be transported further than large or right vales respectively. In light of the "back and forth" movement of valves in intertidal areas, it is difficult to make predictions concerning valve sorting. It should be noted, that no sorting was indicated by the samples of natural valves from the cobble flats.

An interesting observation, made both in field and in the flume, was that as the water level rises, shells (concave down) tend 'bump' expel air bubbles. The trapped air is either totally or partially lost. In either case, the stability of such valves may be affected It was observed that such valves were often transported after losing air. If only some of the air is lost, the valves would become relatively less dense, and more suscepible to transport at a later time. Such bumping may contribute to the dominance of the flood tide in shell transport.

A DISCUSSION OF VALVE TRANSPORT AND DESTRUCTION IN THE STUDY AREA.

Empty pelecypod valves occur throughout the study area. The density and species diversity of empty valves varies with environment, substrate and position within the intertidal zone. The number and diversity of surface valves increase from the upper intertidal mudflats to the lower intertidal cobble flats and bedrock. On the mudflats Macoma balthica valves greatly out number the valves of Mya arenaria and Zyrphaea (probably ice rafted). On the lower intertidal cobble flats, Mya arenaria valves dominate, while in the lower most intertidal the valves of Zyrphaea dominate, but Mya arenaria and Macoma balthica valves are very common (photo #9 and #10).

Macoma balthica occurs in high densities (average 1200/m^2) in the mudflats, while Mya arenaria, which prefers sandy sediments occurs in local populations with moderate densities (100/m^2). It has been determined that great numbers of empty valves should accumulate in the sediment from such live populations. As the number of empty valves produced is very large, and no single mechanism was observed to be dominate, several forces must act to decrease the empty valve numbers. The possible forces include in situ dissolution, transport out of the area, weakening by boring thallophytes, and mechanical destrucion.

In situ dissolution is not strongly supported by field observations; however, the complete lack of valves below 20 cm. strongly suggests the influence of dissolution. Dissolution is not complete, as indicated

Photo # 9 Hole bored by Zyrphaea.

Photo #10 Accumulation of Zyrphaea, Macoma balthica and Mya arenaria valves at low tide.

by the occurrence of surface valves and the abundance of valves within intertidal channels. Mechanisms must exist, therefore, to expose valves from the sediment. As it has been suggested that surface scouring and channel migration are minimal some other mechanism(s) must be important. The existence of these unknown menchanisms has been termed the "Escape Hypotheseis". This hypothesis is based upon several observation:

1. There is a large discrepancy between the live pelecypod population density and the predicted empty valve density.
2. In situ dissolution does not appear to be a dominate mechanism.
3. Channel migration in the study are is insignificant.
4. The presence of empty valves in areas which should be swept free of valves.
5. Valves beening transported are trapped by intertidal channels (even by foot prints).
6. All _Macoma balthica_ valves observed on the mudflat surface were articulated.

The occurrence of articulated valves suggests that the valves are only recently empty. Valves which persisted within the sediment for any length of time would undoubted would undoubtedly have their liagments destroyed. It is therefore suggested that valves 'move' to the sediment surface, soon after the death of the pelecypod. The actual mechanism(s) of movement are not known.

When empty valves appear on the sediment surface they are acted upon by several forces. These are primarily attack by boring thallophytes and transport by tidal currents or intertidal channels, with possible subsequent mechanical valve destruction. A generalization of valve transport and destruction within the study area, can be deduced from field observation:

1. Surface valves tend to be moved in an easterly direction, parallel to the shore, by tidal currents.
2. Movements from one low tide to the next, are either in an easterly or westerly direction.
3. Pelecypod valves are trapped by intervening intertidal channels, and accumulate within them.
4. Valves are normally transported slowly downstream depending on channel competency.
5. In stormy periods, channel sediments and pelecypod valves are swept downstream (J. Moffat, personal communication).
6. The amount of valve breakage increases downstream (Diagram #17).
7. The total number of valves increases downstream.
8. Valve densities and diversities are highest in the lower intertidal zone.
9. The lowermost intertidal has a substrate of cobbles and pitted bedrock, and is therefore uninhabitable by *Mya arenaria* and *Macoma balthica*.

By considering this evidence, general statements may be made concerning pelecypod valve dynamics within the intertidal zone of the study area.

Surface valves are transported in an easterly direction, parallel to the shore. Valves fall into intervening intertidal channels, where they are transported downstream at a rate dependant upon the competency of the channel. These valves are then transported into larger and more competent channels. As they are being transported, valves may be abraded or broken, depending upon the current velocity and nature of the substrate. Valves eventually enter the main channel, where mechanical destruction is greatly increased. Valves are deposited in lowermost intertidal areas, or are plucked from the channel by tidal currents and transported in an easterly direction. From the time the valves appeared upon the surface, they have been weakened by boring thallophytes. The final mechanical destruction of the pelecypod valves takes place in the lowermost intertidal cobble flats and bedrock, during transport by strong tidal currents.

CONCLUSIONS:

1. Shell movement in the study area is eastward along shore in the direction of flood tide.

2.(a) The rate of transport of Left valves is significantly greater than that of Right valves, in the study area.

(b) The rate of transport of Small valves is significantly greater than that of Large valves, in the study area.

3. Pelecypod valves which are moved on the sediment surface, are trapped by even small intertidal channels, from which the shells cannot escape.

4. Shells are slowly moved downstream within intertidal channels during calm weather conditions, but they may be completely flushed into subtidal environments during periods of heavy precipitaion.

5. Pelecypod valves (both articulated and inarticulated) display a strong preferential orientation with respect to current direction within tidal channels and also upon the intertidal flats. Such orientations, however, reflect only the direction of the last current strong enough to orientate them.

6.(a) The loss of pelecypod valves from intertidal sediments is not strictly controlled by the lateral migration of intertidal channels.

(b) The loss of valves from the sediment may be due to 'escape' of valves directly to the sediment surface.

7. The relative amount of valve breakage increases downstream in the large intertidal channel studied.
8. The pattern of _Mya arenaria_ valve breakage in the cobble flat zone is directly related to the relative resistance to breakage of the area impacting upon a cobble and the probability of that area being hit.
9. The decrease in empty valve numbers within the study area is due to: transport into subtidal environments along shore out of the study area, weakening of valves by boring thallophytes (and possibly in situ dissolution), and mechanical destruction during transport.

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