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A COMPARISON OF THE RELATIVE SEDIMENT TRANSPORT OF QUARTZ AND ARAGONITE SAND FOR USE AS BEACH RENOURISHMENT MATERIALS IN SOUTH FLORIDA

BY

BRIAN LEWIS LIPSITZ

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THESIS

OF

BRIAN LEWIS LIPSITZ

Approved:

Thesis Committee

Major Professor Curtis M. Burney

Alan K. Craig

NOVA UNIVERSITY

1987

ABSTRACT

An evaluation of the relative rates of sediment transport of an oolitic aragonite sand and a quartz quarry sand as possible beach renourishment materials has been conducted. When comparing equal volumes, the aragonite experienced less transport than the quartz in both the longshore and in the onshore-offshore directions. When comparing equal size fractions, in sizes 0.35mm and smaller, aragonite was less transportable. The quartz was less transportable in the sizes greater than 0.35mm. This trend was observed in two separate experiments and is attributed to the effective density ratio of aragonite to quartz, dissimilarities in roundness and sphericity, and to differential entrainment and transport of these materials in suspension and bed load within the confines of the inherent bed roughness.

The effective density ratio of aragonite to quartz is highest in the smaller grain sizes and decreases with increasing grain size because the larger aragonitic grains possess fewer oolitic lamellae per grain and resemble their initial biogenic nucleus. In the smaller size fractions where suspension transport is thought to predominate, a larger quartz grain is hydraulically equivalent to a smaller aragonite grain due to the greater density of the aragonite. The aragonite has a higher settling velocity out of suspension and it is less entrainable, due to sheltering effects in the bed matrix allowing a lower position in the velocity profile and a larger reactive angle to the flow. As grain size increases above 0.35mm, the density of the aragonite approaches that of the quartz. The principle of hydraulic equivalence suggests that for two materials of similar density, there should be no difference in the entrainment and transportability between equal size fractions. The preferential transport of the aragonite relative to the quartz in the size fractions greater than 0.35mm is attributed to the difference in their shape, where the rounder aragonite is more easily rolled in traction as the size of both the aragonite and quartz exceed the background bed roughness.

The physical characteristics of aragonite indicate that it has a hydraulic behavior similar to a quartz sand of a slightly larger size. If renourishment is undertaken on John U. Lloyd Beach with aragonite, the most probable source material would be a mining stockpile (mean size 0.52mm) from Ocean Cay in the Bahamas. Based on a theoretical (mean size only) method of the U.S. Army Corps of Engineers, utilization of this stockpile material would reduce the erosion rate on Lloyd Beach by 10%. The results of my study indicate that beach losses could be further reduced by using this aragonite due its higher density. Secondary characteristics such as density and shape of the renourishment material manifest themselves differently in the suspension and bed load modes of transport and should

be considered when choosing a borrow source. Additional transport studies need to be done utilizing larger volumes of material and monitored over a longer time interval.

Acknowledgements

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I am very grateful to my mother, Harriet Lipsitz, for her encouragement and emotional support throughout.

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I. OVERVIEW

Statement of the Problem

The question of comparing alternate sand sources to offshore borrow sites for use in beach renourishment projects has been raised in Florida by the Beach Erosion and Prevention District in Broward County. In the 1976 John U. Lloyd Beach State Recreational Area renourishment project it was originally proposed to use a sand source from one of the many rock quarries located 8-16 kilometers inland from the beach. These deposits represent a series of ancient regressive shorelines. Recently there have been inquiries by the Beach Erosion and Prevention District as to the hydraulic properties and beach suitability of oolitic aragonite, common to much of the Bahamian Islands (Marcona Industries, 1986). There are currently no beaches in the U.S. with naturally occurring or artificially renourished aragonite from which beach stability of this material can be predicted.

This study addresses two specific questions important not only to aragonite beach stability but to the hydraulic properties of sediments in general. When comparing bulk quantities of aragonite to a quarried quartz sand on John U. Lloyd Beach State Recreational Area, which material undergoes the least amount of erosional transport? And secondly, what appears to be the primary and secondary physical characteristics controlling entrainment and transportability of these materials?

Introduction

There can be very little disagreement that Florida's 13,560 kilometers of shoreline are its most precious resource. Two thirds of all tourists coming to Florida (approximately 39 million in 1983) identified the beaches as their most important destination. Tourists spent more than $22 billion in 1985 (Morris, 1985). About half of Florida's extensive barrier islands exhibit serious erosion as they gradually retreat toward the mainland. Because of the current trends in global atmospheric warming and sea level rise, coastal retreat may be on the order of 45 meters during the next 30 to 40 years. Florida's population has grown from 20th largest in the U.S. in 1950 to 7th largest in 1980 and is expected to reach more than 12 million people by the year 1990 (Morris, 1985). The demographics in South Florida are more startling. From 1900 to 1980 the population in this geographic area jumped from 5% to 37% of the state total. Broward County, which contains John U. Lloyd Beach State Recreational Area, has experienced a population growth rate of more than 64% from 1970 to 1980. In 1983-1984, attendance figures in John U. Lloyd Beach State Recreational Area exceeded more than 600,000 visitors (Shoemyen, 1986) making this recreational site one of the most popular in South Florida. Thus, there is ample justification for a strong desire by tourists, residents, and planners alike to maintain and improve the coastal area for both economic and aesthetic reasons.

Although there is agreement between coastal geologists and coastal zone managers as to the causes of beach erosion and barrier island migration, there is a lack of consensus as to the best stabilizing technique. Today's knowledge of proper and prudent coastal engineering practices is much better than in the past where attempts to fortify the beaches against natural forces have only exacerbated the problem. Structures such as jetties, groins, bulkheads, and seawalls tend to increase local erosional effects and to deprive neighboring beaches of vital replenishing sediments. These structures have also disrupted the natural "dynamic equilibrium" between the waves, inherent beach morphology, and sand supply. This is demonstrated by the inability of summer southeast winds to restore coastal sand because a series of beach and inlet protective structures prevents northward movement

The use of artificial beaches as protective and recreational shore structures is becoming increasingly popular. With the adoption of the 1986 Beach Management Plan by the Florida State Legislature, a comprehensive effort has been put forth to examine the possible long-term solutions to Florida's critically eroding beaches and to assign the State Division of Beaches and Shores the responsibility to specify design criteria for beach restoration and renourishment projects. This new law calls for special evaluation of the erosional losses adjacent to navigational inlets and for the establishment of "feeder beaches" that will periodically supplement the flow of sand along particularly sand-starved shorelines. Perhaps of most significance is that the Beach Management Plan places beach renourishment as the primary emphasis and engineering tool in a statewide effort to restore Florida's critically eroding coastline.

Beach renourishment is a relatively new concept in Florida, first put into practice about twenty years ago. The nourishment projects have high initial costs (e.g. the 1976 John U. Lloyd Beach State Recreational Area project cost was approximately $2.7 million) and are designed to include periodic renourishment, usually over seven to ten year cycles. State officials estimate a reserve of 827 million cubic yards of sand in the outer bars and shoals of Florida's inlets (Liefermann and Connelly, 1986). However, due to Army Corps of Engineer restrictions on percent rock and silt content and high transportation costs from remote areas, borrow sources of well-suited fill material are becoming difficult to find. In addition, individual beaches possess their own "fingerprint" grain size distribution, texture, and morphology. The preferred material would be equal to or larger in size than the beach to be restored, containing a low percentage of rock and silt. Potential renourishment materials that are physically smaller or more poorly sorted than native beaches will be expected to be out of equilibrium with the local nearshore wave conditions. These renourished beaches will probably experience significant erosional losses shortly after initial sand emplacement as the nearshore profile re-establishes itself and the finer grain size fractions are winnowed out.

Historical Background

Since the early 1920's when construction began on Lake Mabel (Figure 1) to establish Port Everglades, the coastal area immediately to the south (which currently contains John U. Lloyd Beach State Recreational Area) has undergone a series of dramatic geomorphic and hydrodynamic changes. The discharge location of the New River has changed frequently in the last one hundred years due to numerous storms and hurricane events as well as the construction of Port Everglades in 1926. Prior to 1900, the New River discharged into Lake Mabel and then south some 4 kilometers before entering the sea adjacent to Dania Beach Blvd. (Figure 2). There was also a narrow channel approximately 1.5 kilometers north of Bay Mabel known as the "Haulover" near present day Bahia Mar. This location represented the very first mouth of the New River and later provided portage to small local boats as well as a narrow tidal prism for the New River.

Figure 1

View of Lake Mabel from
the south in 1925

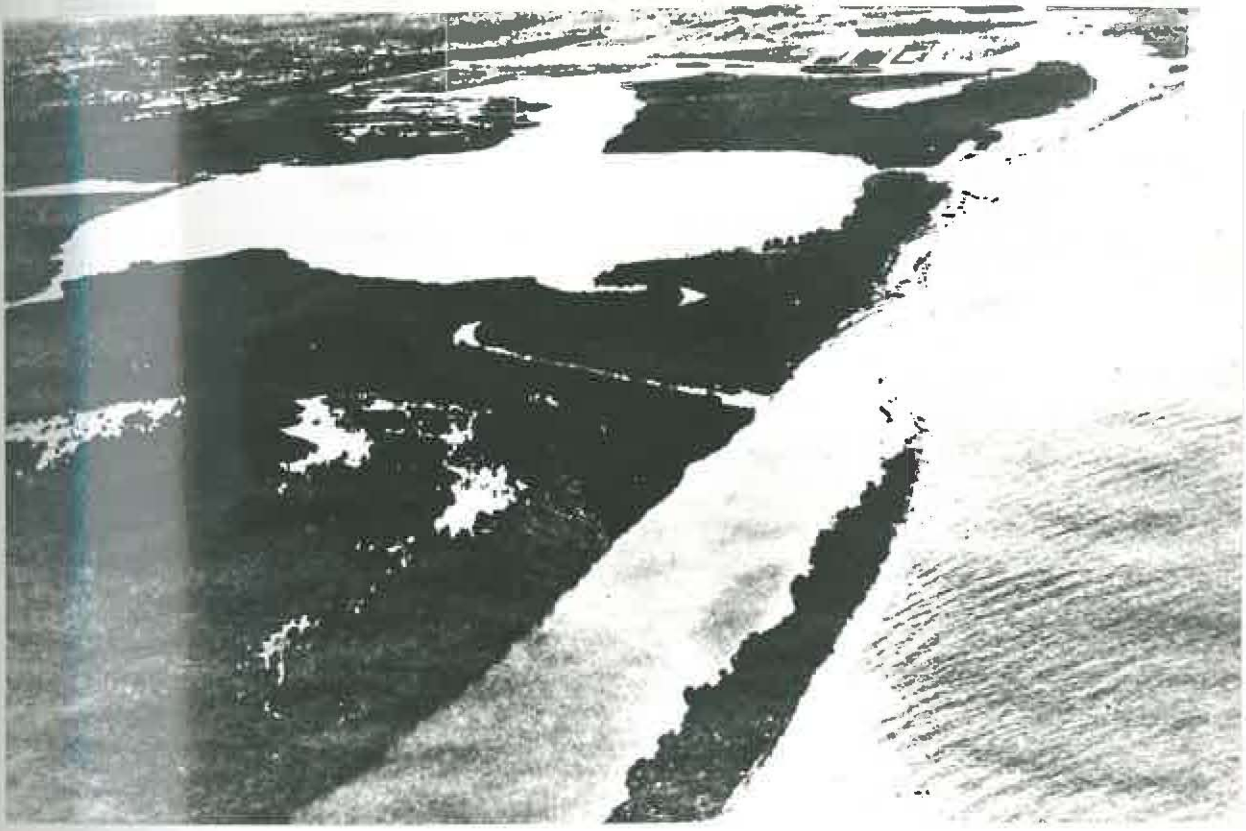
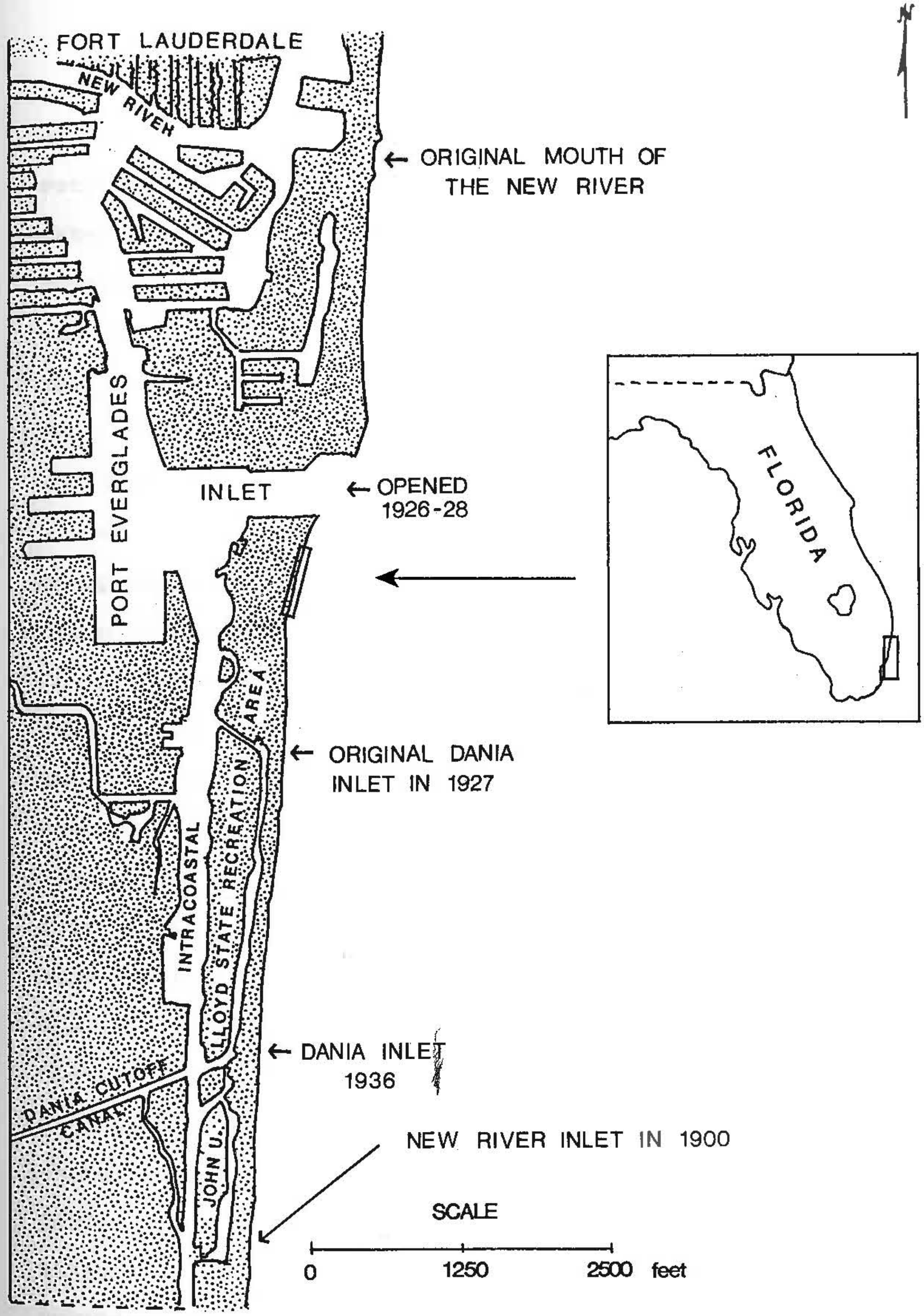


Figure 2

Locations of the New River
Inlet and Dania Inlet
between 1900 and 1937

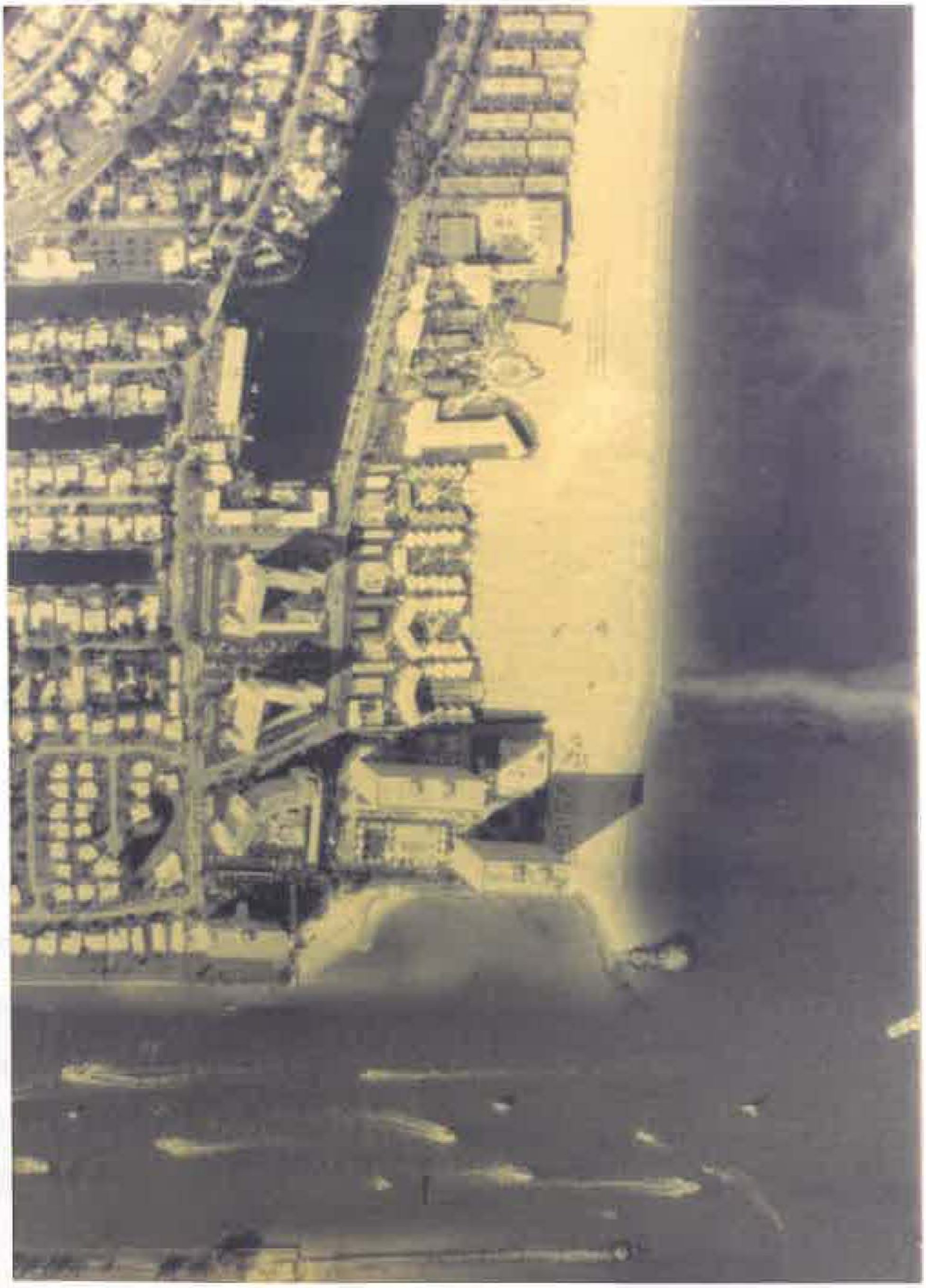

N
FORT LAUDERDALE
NEW RIVER
← ORIGINAL MOUTH OF THE NEW RIVER
PORT EVERGLADES
INLET
← OPENED 1926-28
FLORIDA
← ORIGINAL DANIA INLET IN 1927
INTRACOASTAL
LLOYD STATE RECREATION AREA
← DANIA INLET 1936
DANIA CUTOFF CANAL
JOHN U.
NEW RIVER INLET IN 1900
SCALE
0
1250
2500 feet

In 1900 the New River Inlet 4 km south of Lake Mabel closed naturally and in 1922 dredging began in order to reopen the "Haulover" 1.5 kilometers to the north of Lake Mabel. As construction commenced to establish Port Everglades in 1926, the drainage network of the New River was altered as was its associated sedimentation pattern. The Port channel became the major discharge site for the New River and because of this the "Haulover" to the north continued to be filled with sediment until it completely closed in 1937. The emplacement of protective breakwaters (perpendicular to the shore) north and south of Port Everglades channel was to have greatest detrimental impact on present day John U. Lloyd Beach State Recreational Area. The sediment load from the New River, though small in volume, no longer was being transported south of the channel. More significantly however, the breakwaters impeded the natural southerly littoral drift. It is clear from 1984 aerial photographs that the breakwaters (now submerged) still exert an effect on the littoral drift system by continuing to accumulate sand, especially on the northern side of Port Everglades channel (Figure 3).

Another interesting coastal feature along this shoreline was the development of the Dania Inlet in the mid 1920s (Figure 2). In 1927 it was located approximately 1.5 kilometers south of Port Everglades channel near the northern extent of present day Whiskey Creek in John U.

Figure 3

Accumulation of sand on the
submerged breakwater north
of Port Everglades Inlet



Lloyd Beach State Recreational Area. By 1936, a prograding spit from the north had effectively sealed it off and a new Dania Inlet was breached about 1.5 kilometers south of its original location (Univ. of Florida, 1968). With the closure of the Dania Inlet around 1940, the coastline adjacent to Port Everglades assumed a configuration much the same as it exists today. Within 10 years prior to construction of Port Everglades there was extensive prograding spit development immediately north of Port Everglades Inlet. Since the competence and capacity of the New River is known to have been minimal, large quantities of sand must have been transported south during these years in the littoral drift system. Based on climatic trends and the sediment dynamics in this area, it appears that the most serious contributors to the beach erosion problem in John U. Lloyd Beach State Recreational Area are (1) the combined effects of coastal inundation by sea level rise (approximately 0.25 cm per year) associated with global climatic warming and (2) the continued starvation of sediment to this beach, a condition found on all beaches downdrift of protected inlet channels.

Net losses of beach material in Lloyd Park since Port Everglades was constructed have been substantial. From 1928-1977 it is estimated that the beach has retreated approximately 17 meters or an average of 0.3 meters per year (annual beach losses > 42,000 cubic meters per year

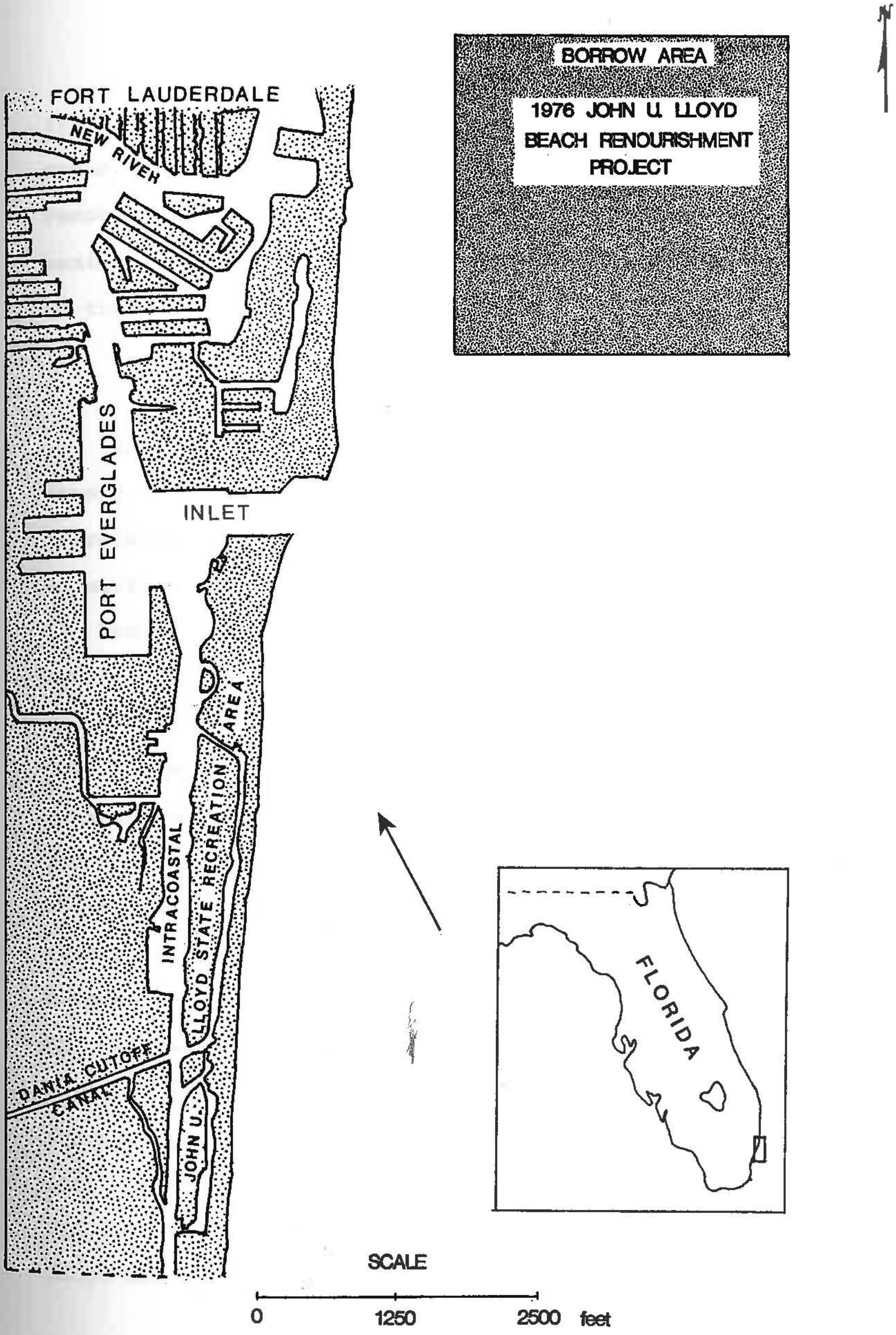
(U.S. Army Corps of Engineers, 1978). Of the approximate 38,000 cubic meters of material transported south in the littoral drift system to Port Everglades Inlet, half of this amount has been accreting on the beach north of the inlet with almost all of the remainder shoaling in the inner and outer channel (Coastal Planning & Engineering, Inc.(CPE), 1985). Although more of the drift material is being transported around the north jetty as the recently constructed northern jetty spur (1979) becomes saturated with sand, it is estimated that a mere 1200-1500 cubic meters of sand per year is replenishing Lloyd Park beach (CPE, 1985). Other reports (U.S. Army Corps of Engineers, 1963) estimate that the inlet itself may capture as much as 15,000 cubic meters of sand per year. Studies in Florida by the Coastal Engineering Research Center in 1969-1973 (DeWall, 1977) and by Suboceanic Consultants in 1977 which were based on weekly Littoral Environment Observation (LEO) programs calculated the northerly and southerly transport to be nearly equal over an annual cycle (U.S. Army Corps of Engineers, 1978). An examination of the long-term shoreline changes adjacent to Port Everglades indicates net erosional losses confirming that the beach's response to periodic extreme events, especially northeasterly winter storms, must be substantial. The northern end of Lloyd Park, which is bounded by the south jetty of Port Everglades Inlet has experienced more severe erosion than in the southern half since the port channel was opened in 1928. This is probably due in part to increased scouring as waves are diffracted around the jetty and in part because sand transported south most likely arrives at the beach in the southern reaches.

In 1962 nearly 383,000 cubic meters of sand were dredged from the entrance channel to Port Everglades and stockpiled along 1036 meters of John U. Lloyd Beach State Recreational Area (CPE, 1985). A much larger effort took place to artificially renourish the beach in 1976/1977. In the northern 1.0 kilometer zone of the park, 834,000 cubic meters of sand were emplaced at a cost of $2.7 million. The borrow site was located in a 2.6 square kilometer area about 0.8 kilometers north of Port Everglades channel (Figure 4). According to 1984 surveys (CPE, 1985), 423,000 cubic meters of sand have been lost from the beach since 1976 or slightly more than 50% in eight years since its initial emplacement.

In 1986 the Florida Legislature appropriated a record $12.2 million to fund erosion control projects in fiscal year 1986-87. Of the $3.3 million earmarked to fully funded projects, John U. Lloyd Beach State Recreational Area is to receive $1.6 million this year for renourishment purposes (Florida Shore and Beach Preservation Assoc. Newsletter, Summer 1986). It is hoped that the results of this thesis can be of some assistance in determining the

Figure 4

Location of borrow site for
the 1976 John U. Lloyd Beach
State Recreation Area
renourishment project


BORROW AREA
1976 JOHN U. LLOYD
BEACH RENOURISHMENT
PROJECT
N
FORT LAUDERDALE
NEW RIVER
PORT EVERGLADES
INLET
INTRACOASTAL
JOHN U. LLOYD STATE RECREATION AREA
DANIA CUTOFF CANAL
FLORIDA
SCALE
0
1250
2500 feet

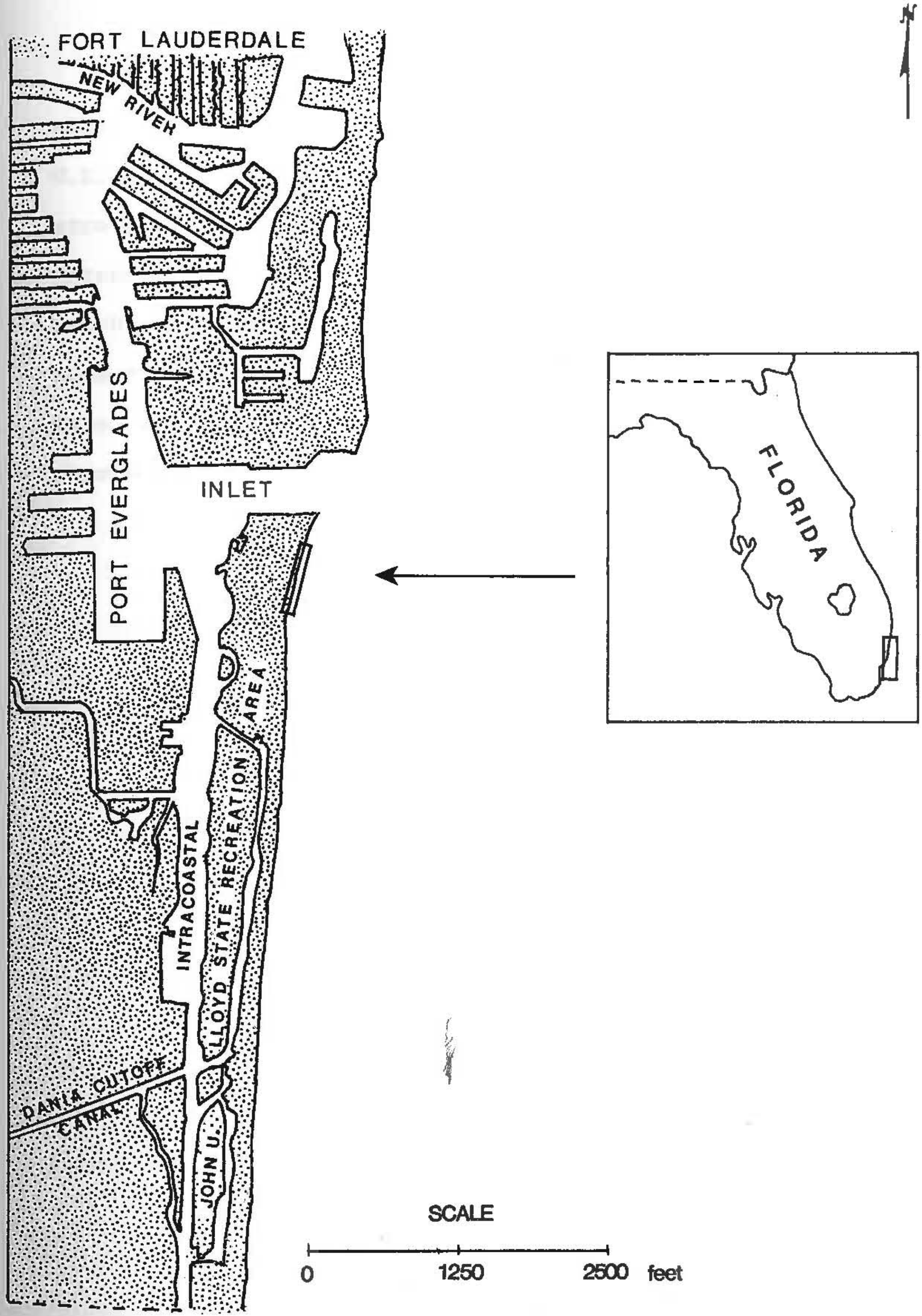
type of borrow material chosen for John U. Lloyd Beach State Recreational Area, help to minimize future renourishment needs on this beach, and in doing so, maximize the time before restoration will be needed again in the future.

Location and Setting

The field site of this thesis is located in Broward County, Florida, approximately 450 meters south of the Port Everglades channel (Figure 5). The channel is situated 18 kilometers south of Hillsboro Inlet and 21 kilometers north of Bakers Haulover Inlet. Typical rainfall in this subtropical area is between 125 and 155 centimeters per year. Average yearly temperature is 24 degrees Celsius (U.S. Army Corps of Engineers, 1978). The coastline experiences winds predominantly from the east, northeast, and southeast with strong northeasters (common from October to December) and balmy east to southeasterly breezes in the spring and summer. Much of the seasonal wind effects are dampened due to the sheltering nature of the Bahama Banks to the east and northeast (U.S. Army Corps of Engineers, 1978). Although typical nearshore plants such as sea oats (Uniola paniculata) and sea grapes (Cocoloba uvifera) can be found, the vegetation consists primarily of Australian Pine (Casuarina equisetifolia) within John U. Lloyd Beach State Recreational Area.

Figure 5

Location of thesis field site
in John U. Lloyd Beach State
Recreation Area


N
FORT LAUDERDALE
NEW RIVER
PORT EVERGLADES
INLET
INTRACOASTAL
JOHN U.
LLOYD STATE RECREATION AREA
DANIA CUTOFF CANAL
FLORIDA
SCALE
0
1250
2500 feet

The southeast coast of Florida consists of relatively wide, flat coastal terraces and barrier islands. John U.Lloyd Beach State Recreational Area has a more or less straight coastline separated from the mainland by the Intracoastal Waterway. The shoreline consists of Holocene beach and dune sands underlain by coral and algal formations dating from the Miocene to the Pleistocene. This configuration is fronted to the east by a rather narrow continental shelf of about 2.4 kilometers.

II. MATERIALS

Source and Description of Materials

Two materials, a quartz and aragonite beach sand were examined to determine their physical characteristics (grain size, shape, composition, and density). Subsequently, each was stained with a fluorescent dye tracer. Next, these sands were emplaced at the test site for identification of their direction and relative magnitude of transport in the intertidal zone. The following is a description and comparison of the sedimentary statistics and physical characteristics of these materials along with background on tracer preparation, experimental field design, and lab procedures used to obtain the raw sediment transport data.

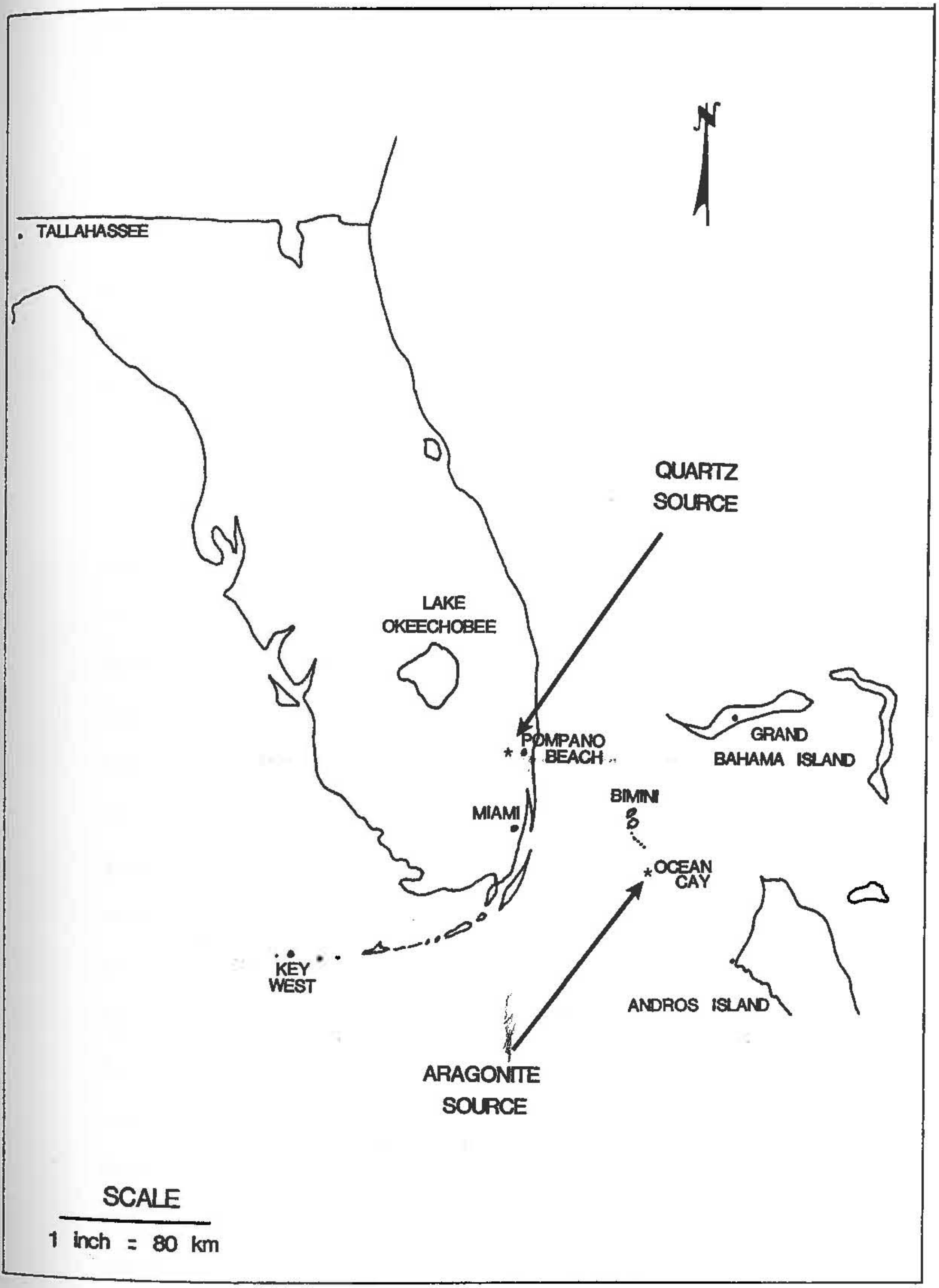
Aragonite Sand Source

Commercial aragonite mining is conducted in the Bahamas (approximately 80 kilometers east of Miami) on Ocean Cay, (Figure 6) by Marcona Ocean Industries. This company has a lease with the Bahamian government for deposits roughly quantified at 100 billion tons. Prior to shipment from the Bahamas, the sand is screened to eliminate large shells and rocks which are aesthetically undesirable and potentially dangerous to beach users.

Oolitic aragonite is precipitated naturally in the Bahamas as colder waters that are saturated with calcium carbonate interact with the warm waters of the Gulf Stream

Figure 6

Location of aragonite mining site on Ocean Cay in the Bahamas and quartz source area in Pompano Beach, Florida


N
TALLAHASSEE
QUARTZ SOURCE
LAKE OKEECHOBEE
POMPANO BEACH
GRAND BAHAMA ISLAND
BIMINI
MIAMI
OCEAN CAY
KEY WEST
ANDROS ISLAND
ARAGONITE SOURCE
SCALE
1 inch = 80 km

on the Great Bahama Banks. The resulting calcium carbonate grains are oolitic (egg shaped), near white in color, and very well rounded, and have a specific gravity as high as 2.88 (Marcona Ocean Industries, 1986). It is suggested by Marcona Industries that aragonite's outstanding sphericity provides a greater resistance to motion and its high density causes faster settling out of suspension than quartz sand.

Quartz Sand Source

A second approach to identifying an alternate borrow material was to examine a quartz sand from one of the many rock quarries located 8-16 kilometers west of the beach. The quartz sample chosen came from the 101 Sand & Fill operation in Pompano Beach, Florida, located in northwest Broward County approximately 40 kilometers inland from John U. Lloyd Beach State Recreational Area (Figure 6). This fine-grained sand was removed from a distinctive horizon at the nineteen foot excavation level and has a very-well sorted, sugary texture with larger intermixed marine bivalve and molluscan shells. It ranges in color from tan to light gray and upon closer examination shows an angular, conchoidal shape even in the smallest grain sizes. The amount of calcium carbonate ranges from 0-10% approaching zero in the finest size fractions. A detailed survey would need to be undertaken to precisely delineate the total volume present and test for variability in silt and rock content. The samples showed almost no material larger than pebble size with the exception of some well-preserved bivalve shells.

Grain Size Distribution

Many techniques are available for the definition of grain size in sediments. These include pipette sedimentation, sieving, thin section analysis, and direct loose grain measurement (e.g. Krumbein and Pettijohn, 1938; Milner, 1962). Grain size distributions for the aragonite, quartz, and Lloyd Park beach samples in this study were obtained by sieving, using standardized procedures based on Krumbein and Pettijohn (1938) and Folk (1968). After washing and oven drying, samples were split to approximately 30-50 grams using a Jones-type splitter and placed in a set of eight inch U.S. Bureau of Standards brass sieves (#5 - #325) ranging in screen opening from 4.00mm to 0.063mm (-2.0 phi to 4.0 phi at half phi intervals). All of the grain size results were quantified using the Phi Scale (Krumbein, 1938) defined as: Size (phi) = $-\log_2 d$ where d equals the grain diameter in millimeters. Thus, the smaller the phi number the larger the grain diameter. After the screens were shaken for 15 minutes on a Ro-Tap shaker, the remaining mass on each was weighed to generate cumulative and frequency percent curves. The cumulative curves generate all statistical parameters directly and the shape of the curve is independent of the sieves used. The frequency curve is independent of the sieve interval and although it cannot generate statistical parameters directly it gives excellent visual comparisons between weight percentiles for different materials. It is generally recognized (Griffiths, 1967) that for most particles, the behavior on a sieve is determined largely by the intermediate diameter of the grain which according to Rittenhouse (1941, 1943) can show a considerable range. Despite this difficulty, the variation in repeated analyses of the same samples in the same and in different laboratories has been shown to be negligible (Walker, 1941).

Tables 1 through 5 present summations of the grain size statistics for the aragonite, quartz, and Lloyd Park beach samples. Two samples each were processed for the quartz and aragonite due to their relative uniformity. Because of higher variability in the Lloyd Beach material, three sieve analyses were completed. The Lloyd Beach sediments were removed along transects perpendicular to the shoreline ranging from the dune scarp down to the -0.91 meter bathymetric contour at mean high tide. Two separate techniques were used to quantify the grain size distributions: 1) moment measures (Folk, 1968) which (strictly computational) statistically weights each grain size fraction in the distribution according to its abundance, and 2) graphic measures resulting from the

TABLE 1

SUMMARY OF GRAIN SIZE STATISTICS BY MOMENT MEASURES

Sample	Phi Mean (mm)		Phi Std.Dev (mm)	
Qtz	1.967	(0.256)	1.062	(0.479)
Qtz-B	1.989	(0.252)	1.113	(0.462)
Arag	1.929	(0.262)	0.970	(0.510)
Arag-B	1.886	(0.271)	0.989	(0.504)
Lloyd	1.458	(0.364)	0.971	(0.510)
Lloyd-A	1.050	(0.483)	1.201	(0.435)
Lloyd-CE	1.100	(0.467)	1.110	(0.464)

Average Values

Sample	Phi Mean (mm)		Phi Std. Dev.(mm)	
Lloyd Beach	1.203	(0.434)	1.094	(0.468)
Aragonite	1.908	(0.267)	0.980	(0.507)
Quartz	1.978	(0.254)	1.088	(0.471)

TABLE 2

SUMMARY OF GRAIN SIZE DISTRIBUTION

Folk and Ward (1957) Statistics

Sample	Phi Mean	Phi St.Dev.	Skewness	Kurtosis
Qtz	2.26	0.85	-0.162	1.536
Qtz-B	2.11	0.97	-0.238	1.884
Arag	2.00	0.94	-0.109	1.110
Arag-B	2.00	0.95	-0.109	1.154
Lloyd	1.51	0.93	-0.376	1.237
Lloyd-A	1.16	1.11	-0.222	0.896
Lloyd-CE	1.16	1.06	-0.336	1.145

Average Values

Sample	Phi Mean(mm)	Phi Std.Dev.(mm)	Skewness	Kurtosis
Quartz	2.185 (0.220)	0.910 (0.532)	-0.200	1.710
Aragonite	2.00 (0.250)	0.945 (0.519)	-0.109	1.132
Lloyd Beach	1.277 (0.413)	1.033 (0.489)	-0.311	1.093

TABLE 3

SUMMARY OF GRAIN SIZE DISTRIBUTION

Inman (1952) Statistics

Sample	Phi Mean	Phi Std.Dev	Skewness	Kurtosis
Qtz	2.08	0.71	-0.056	1.296
Qtz-B	2.10	0.72	-0.055	1.778
Arag	1.99	0.87	-0.023	0.914
Arag-B	1.99	0.88	-0.023	0.920
Lloyd	1.41	0.91	-0.330	0.725
Lloyd-A	1.12	1.11	-0.117	0.644
Lloyd-CE	1.07	1.01	-0.267	0.812

Average Values

Sample	Phi Mean(mm)	Phi Std.Dev(mm)	Skewness	Kurtosis
Aragonite	1.99 (0.252)	0.875 (0.545)	-0.023	0.917
Quartz	2.09 (0.235)	0.715 (0.609)	-0.056	1.537
Lloyd Beach	1.20 (0.435)	1.01 (0.496)	-0.238	0.727

TABLE 4

SUMMARY OF GRAIN SIZE DISTRIBUTION

Trask (1932) Statistics

Sample	Mean (mm)	Std.Dev (mm)	Skewness	Kurtosis
Qtz	0.250	0.547	1.080	0.218
Qtz-B	0.243	0.547	1.049	0.203
Arag	0.278	0.426	1.052	0.268
Arag-B	0.276	0.435	1.045	0.241
Lloyd	0.347	0.486	1.130	0.160
Lloyd-A	0.523	0.314	1.127	-0.251
Lloyd-CE	0.476	0.403	1.189	0.183

Average Values

Sample	Mean(mm)	Std.Dev(mm)	Skewness	Kurtosis
Aragnite	0.277	0.430	1.048	0.254
Quartz	0.246	0.547	1.064	0.210
Lloyd Beach	0.449	0.401	1.149	0.031

TABLE 5

TRASK SORTING COEFFICIENT

Sample	Sorting Coef. (So)
Arag	1.532
Arag-B	1.516
Qtz	1.352
Qtz-B	1.352
Lloyd	1.434
Lloyd-A	1.784
Lloyd-CE	1.575

Sample	Mean Sorting Coef. (So)
Aragonite	1.524
Quartz	1.352
Lloyd Beach	1.598

cumulative and frequency percent curves based on the methods of Folk and Ward (1957), Inman (1952), and Trask (1932). Graphic measures utilize select quartiles of the size distribution (e.g. 16th, 50th, & 84th for Folk and Ward, 1957) and weight them equally in the case of the mean size or weight them differently by inserting coefficients as in the case of the skewness and kurtosis parameters. For a full description of the raw data see Appendix A.

Figures 7 through 14 give visual representations of the graphics data. The calculated mean grain size for the three materials will be taken as follows:

Lloyd Beach	0.434mm	(1.203 phi)
Aragonite	0.267mm	(1.908 phi)
Quartz	0.254mm	(1.978 phi)

It is believed that moment measures give the best size approximation because every grain size interval in the distribution is weighted into the formula. Folk and Ward (1957) incorporated only 3 quartiles and Inman (1952) and Trask (1932) both utilized two quartile measurements on the graphics curve making these methods less precise despite being rapid, simple approaches.

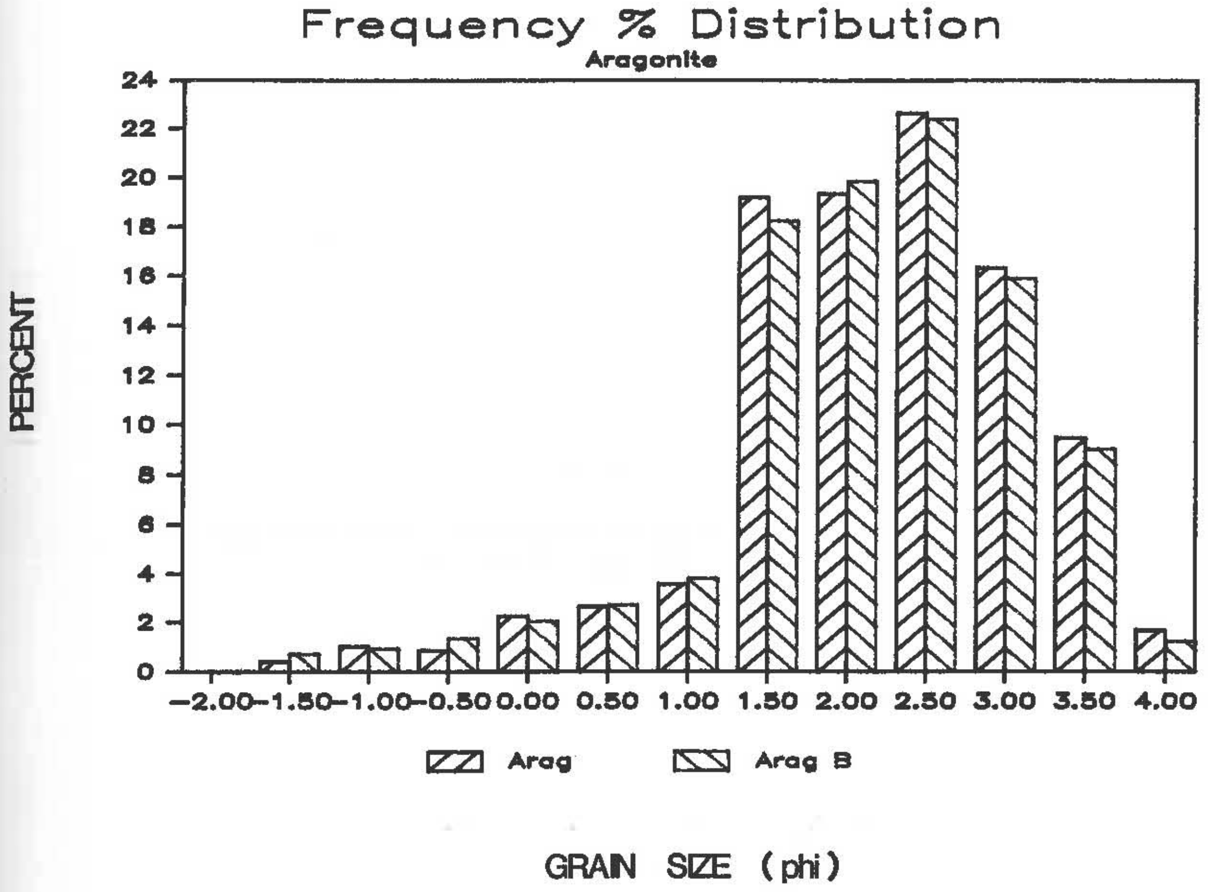
A second parameter of geological significance is the dispersion about the mean or standard deviation. It describes the size uniformity or sorting of the sediment. Typically, beach sands are very well sorted sediments with very few grains larger than 2.00mm (-1.0 phi) or smaller

Figure 7

Frequency percent distribution
of aragonite

Figure 8

Cumulative percent distribution
of aragonite


Frequency % Distribution
Aragonite
PERCENT
24
22
20
18
16
14
12
10
8
6
4
2
0
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
▨ Arag
▧ Arag B
GRAIN SIZE (phi)

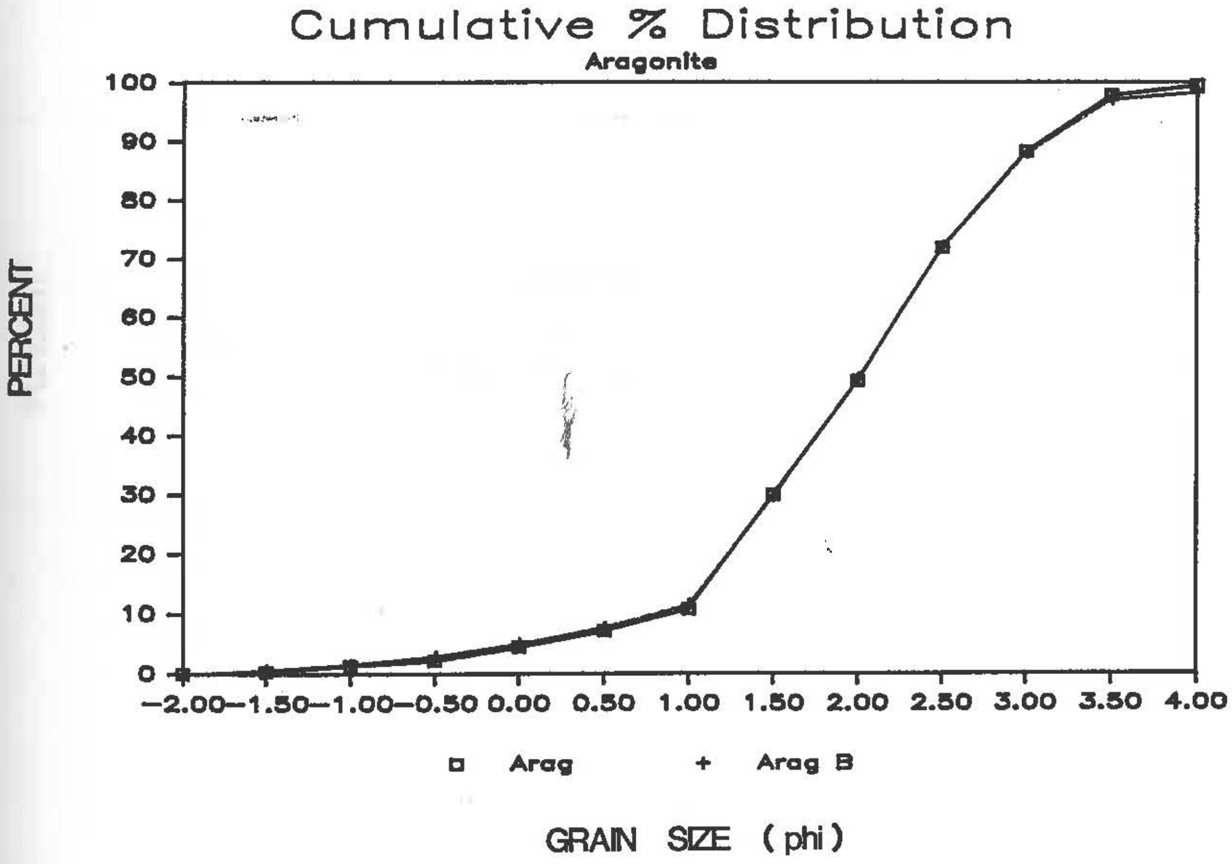
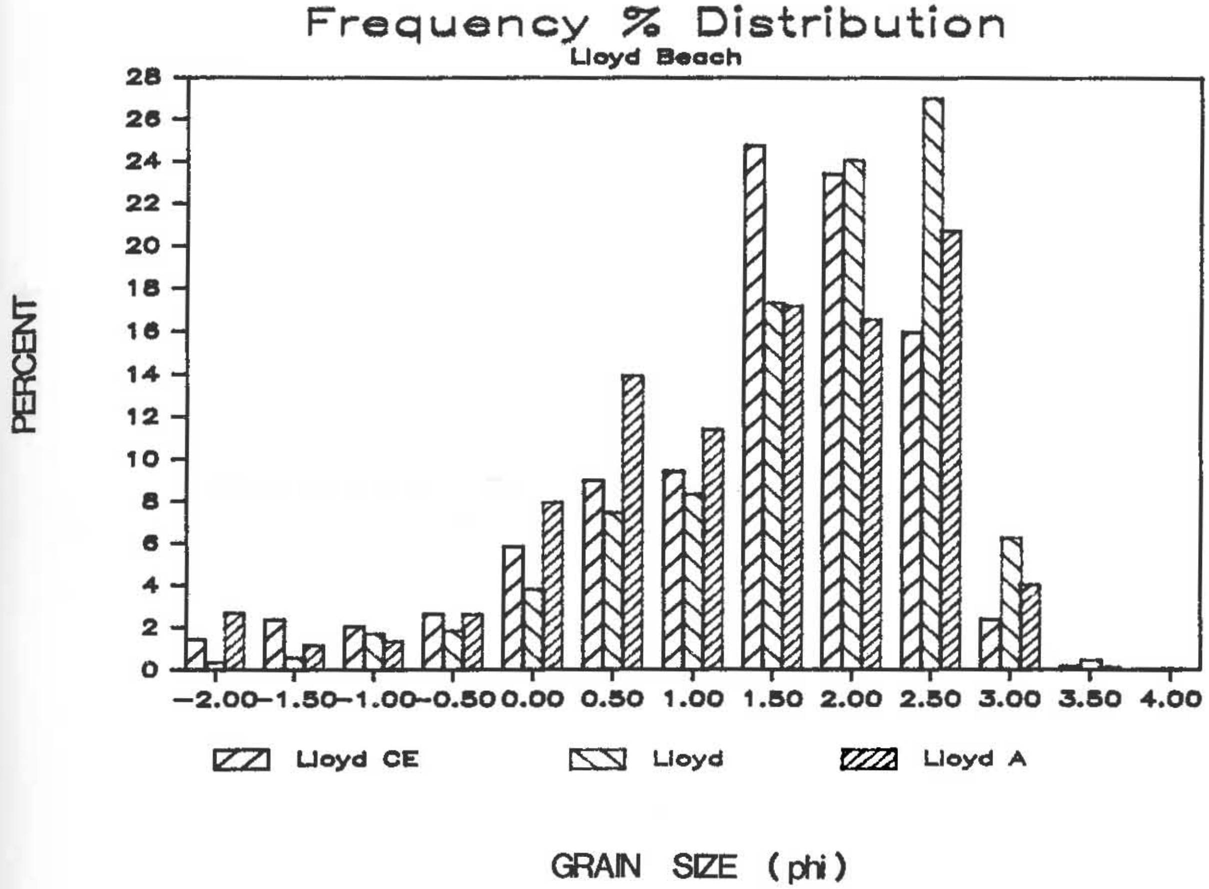

Cumulative % Distribution
Aragonite
PERCENT
100
90
80
70
60
50
40
30
20
10
0
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
□ Arag
+ Arag B
GRAIN SIZE (phi)

Figure 9

Frequency percent distribution
of Lloyd Beach

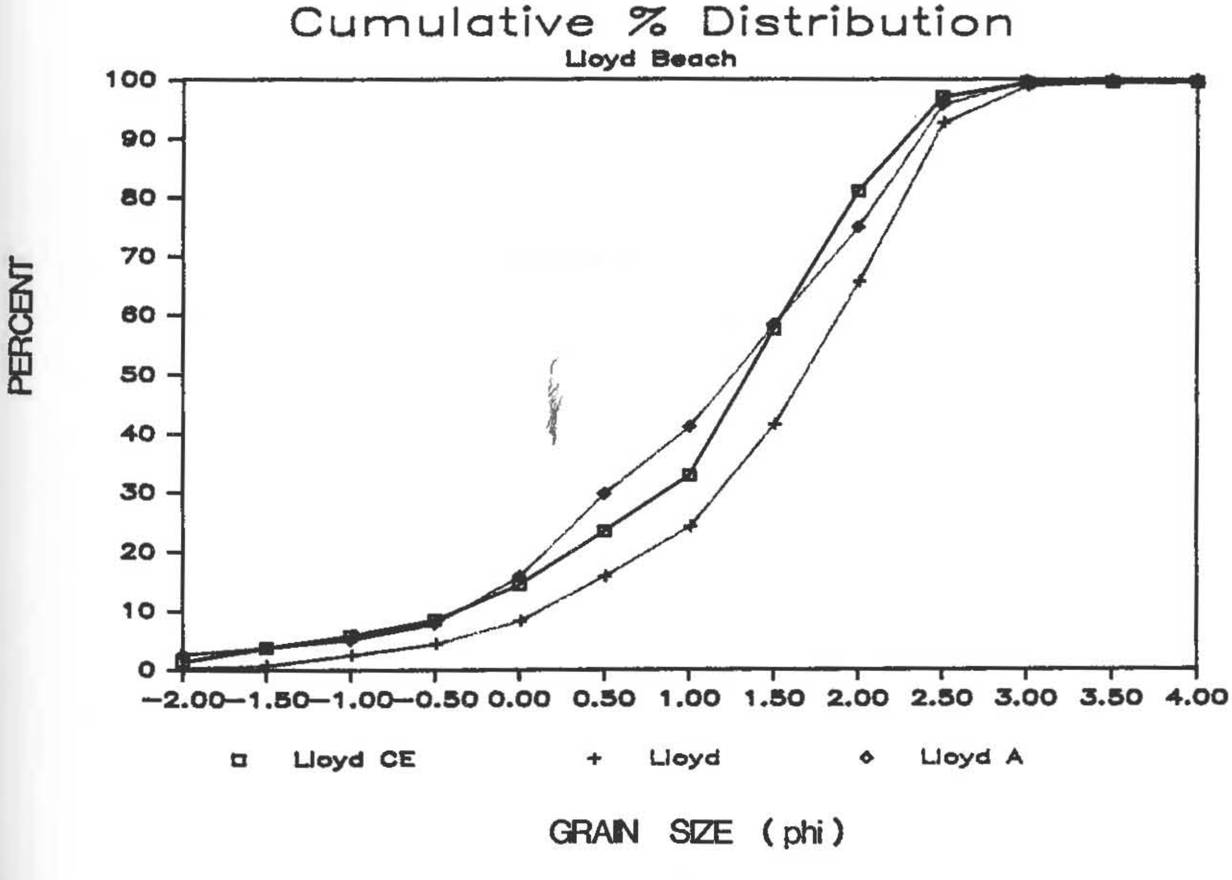
Figure 10

Cumulative percent distribution
of Lloyd Beach



Frequency % Distribution

Lloyd Beach



Cumulative % Distribution

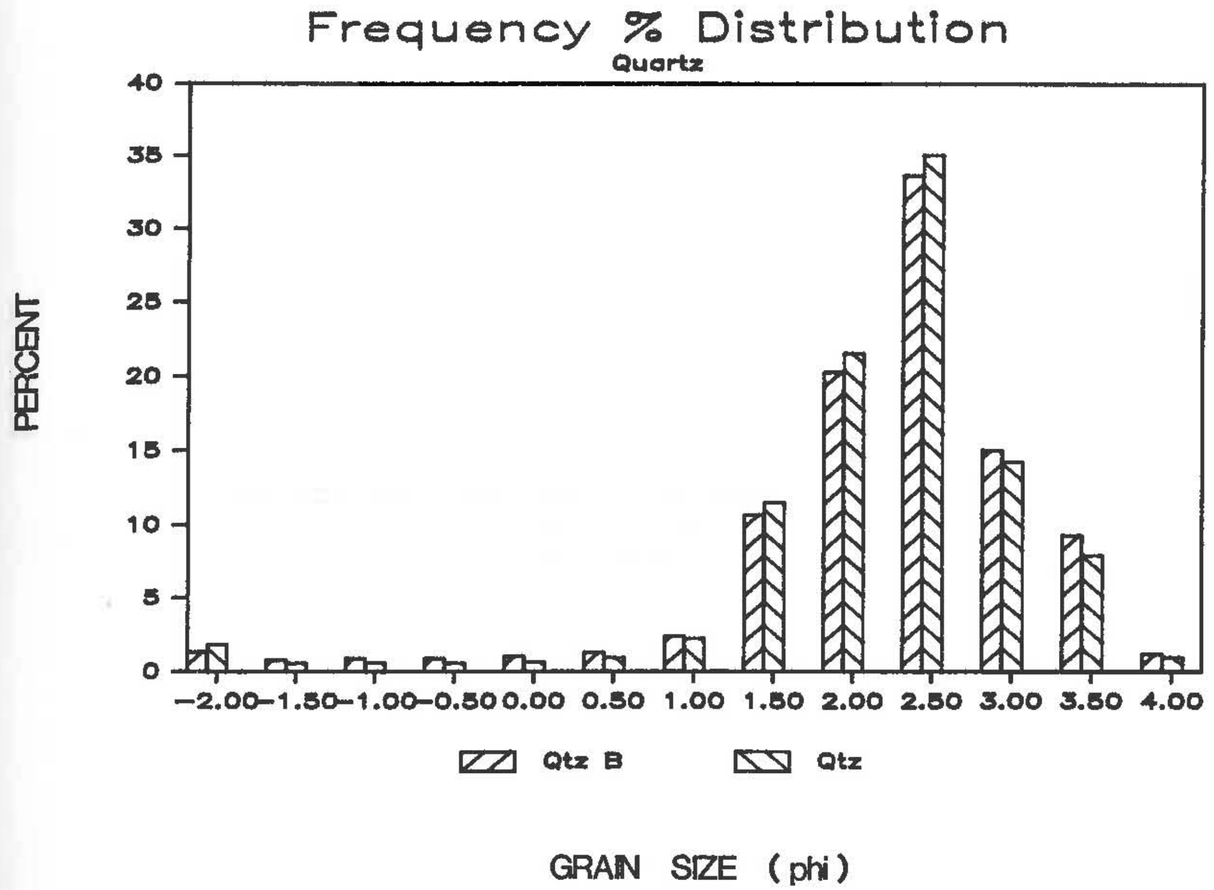
Lloyd Beach

Figure 11

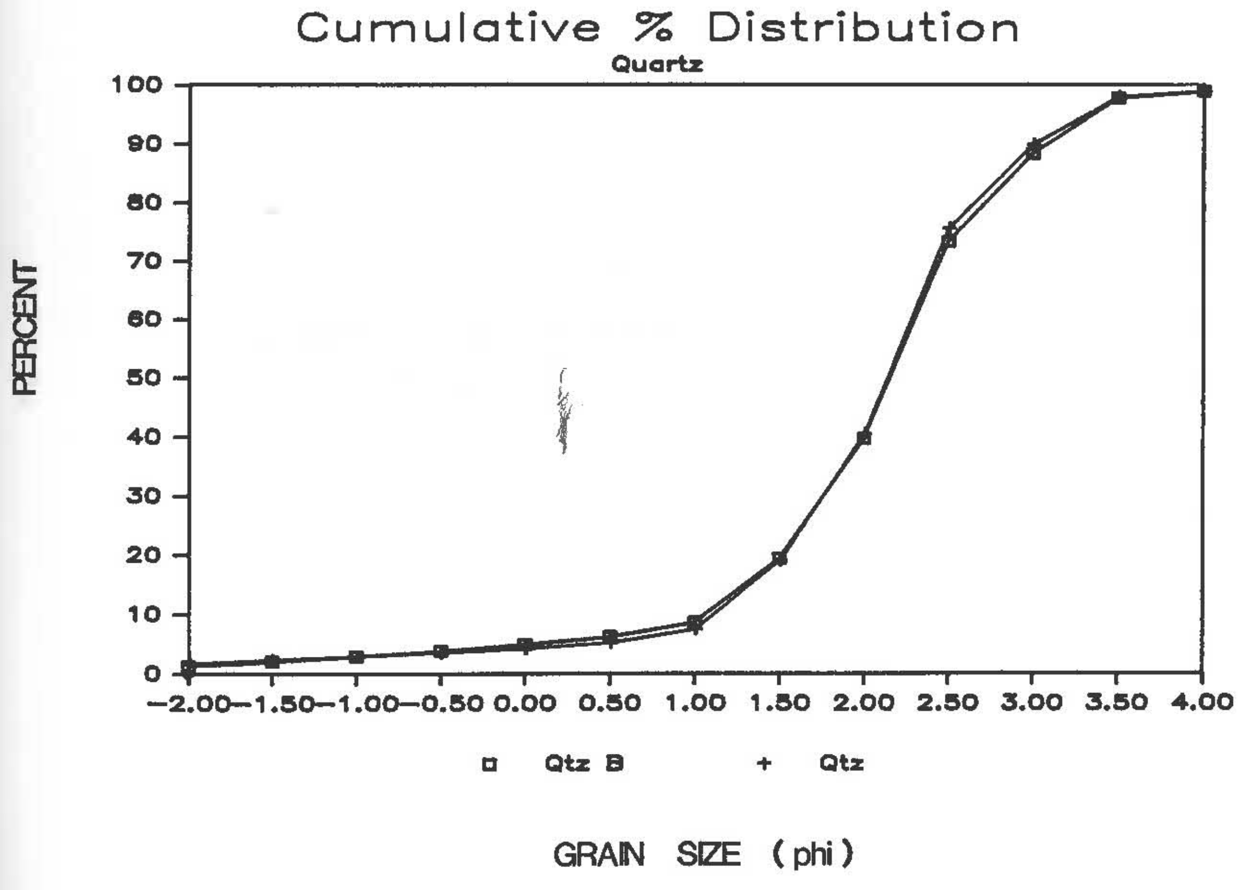
Frequency percent distribution
of quartz

Figure 12

Cumulative percent distribution
of quartz


Frequency % Distribution

Quartz


Cumulative % Distribution

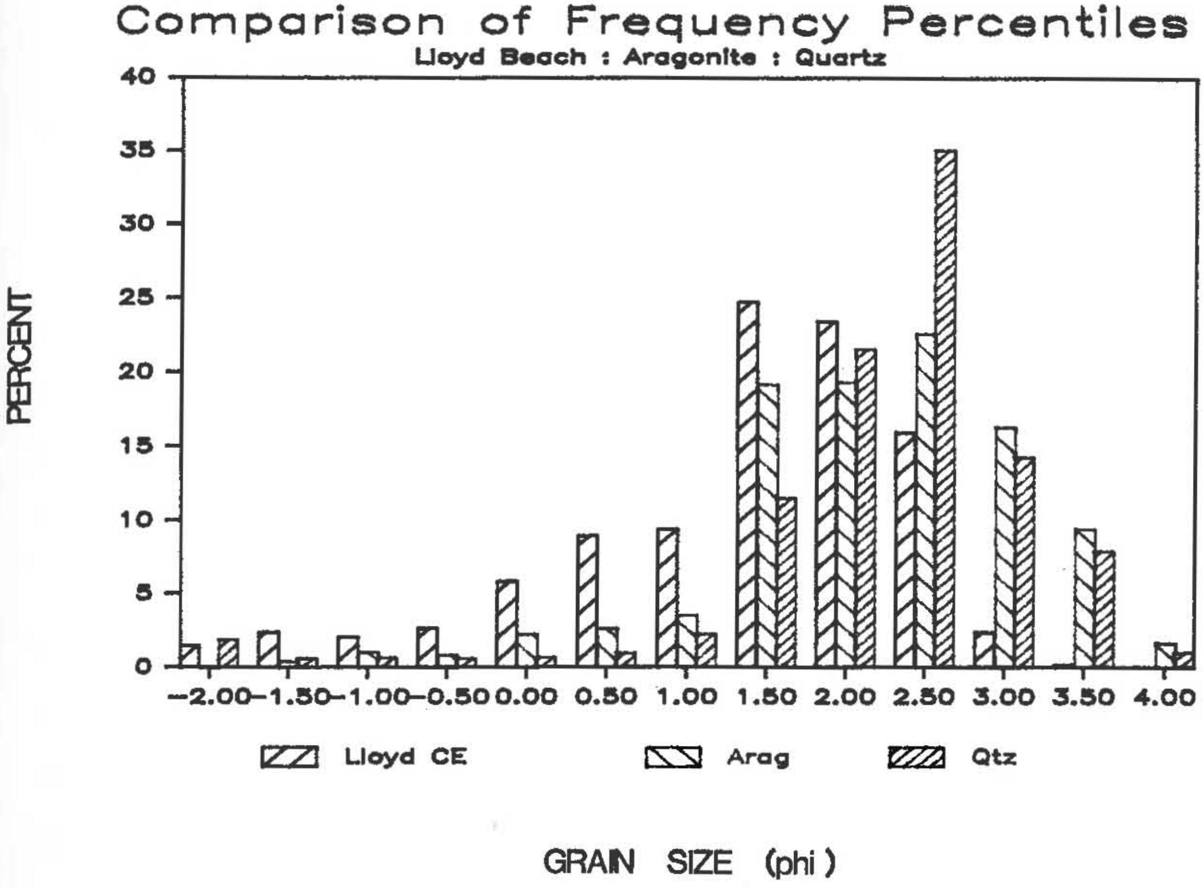
Quartz

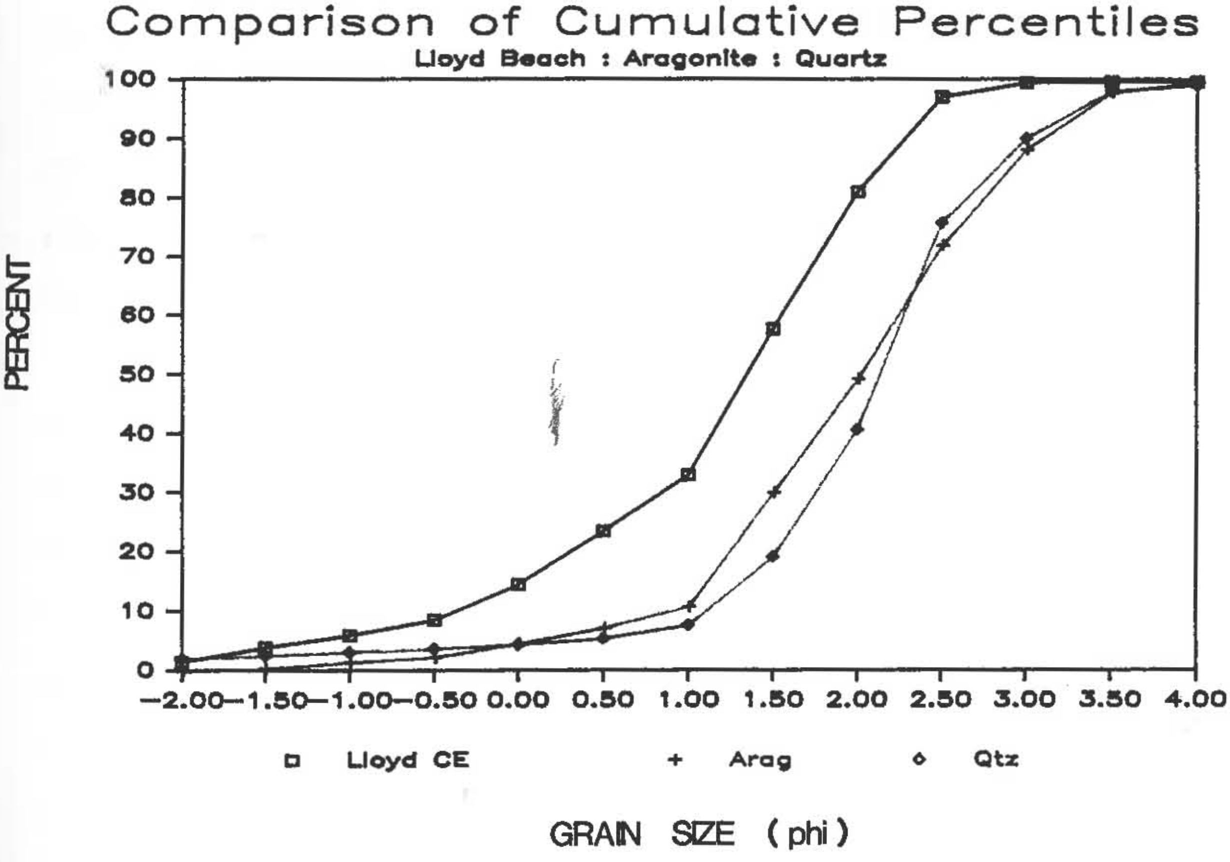
Figure 13

Frequency percent comparison
between aragonite, quartz,
and Lloyd Beach

Figure 14

Cumulative percent comparison
between aragonite, quartz,
and Lloyd Beach


Comparison of Frequency Percentiles
Lloyd Beach : Aragonite : Quartz
PERCENT
40
35
30
25
20
15
10
5
0
−2.00
−1.50
−1.00
−0.50
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Lloyd CE
Arag
Qtz
GRAIN SIZE (phi)


Comparison of Cumulative Percentiles
Lloyd Beach : Aragonite : Quartz
PERCENT
100
90
80
70
60
50
40
30
20
10
0
−2.00
−1.50
−1.00
−0.50
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
□ Lloyd CE
+ Arag
◇ Qtz
GRAIN SIZE (phi)

than 0.063mm (4.0 phi). In the past, the most commonly reported formula used was based on the sorting coefficient of Trask (1932) which considers the central portion of the curve and yields a dimensionless coefficient for comparing the degree of sorting between various sediments. According to this method, a typical beach sand should have a sorting coefficient (So) from 1.3 to 1.5. The lower the So value, the better sorted the sample. Results from the three beach materials (Table 5) indicate that aragonite, quartz, and Lloyd Beach sand are "typical" with the Lloyd Beach material moderately sorted for a beach sand. All three materials would be classified as well sorted sediments with So values < 2.5. All of the methods applied to the data generate very similar sorting characteristics between the three test materials with perhaps the quartz showing the best overall size sorting. The uniform appearance of the quartz and aragonite compared to the Lloyd Beach sand is probably due to their smaller mean grain size and homogeneous composition.

Data on the skewness and kurtosis (both dimensionless coefficients of these distributions) gives additional information on how these beach sands might react to incipient waves. The skewness measures the displacement of the median from the "x" midpoint or in the case of sediments, whether there is an excess of fine material (positively skewed) or an excess of coarse material (negatively skewed). Since the method of Folk and Ward (1957) includes 90% of the distribution and takes in the sensitive "tails" of the curve, the following are representative skewness values based on this method:

Lloyd Beach	-0.311	coarse/strongly coarse skewed
Aragonite	-0.109	near symmetric
Quartz	-0.200	coarse skewed

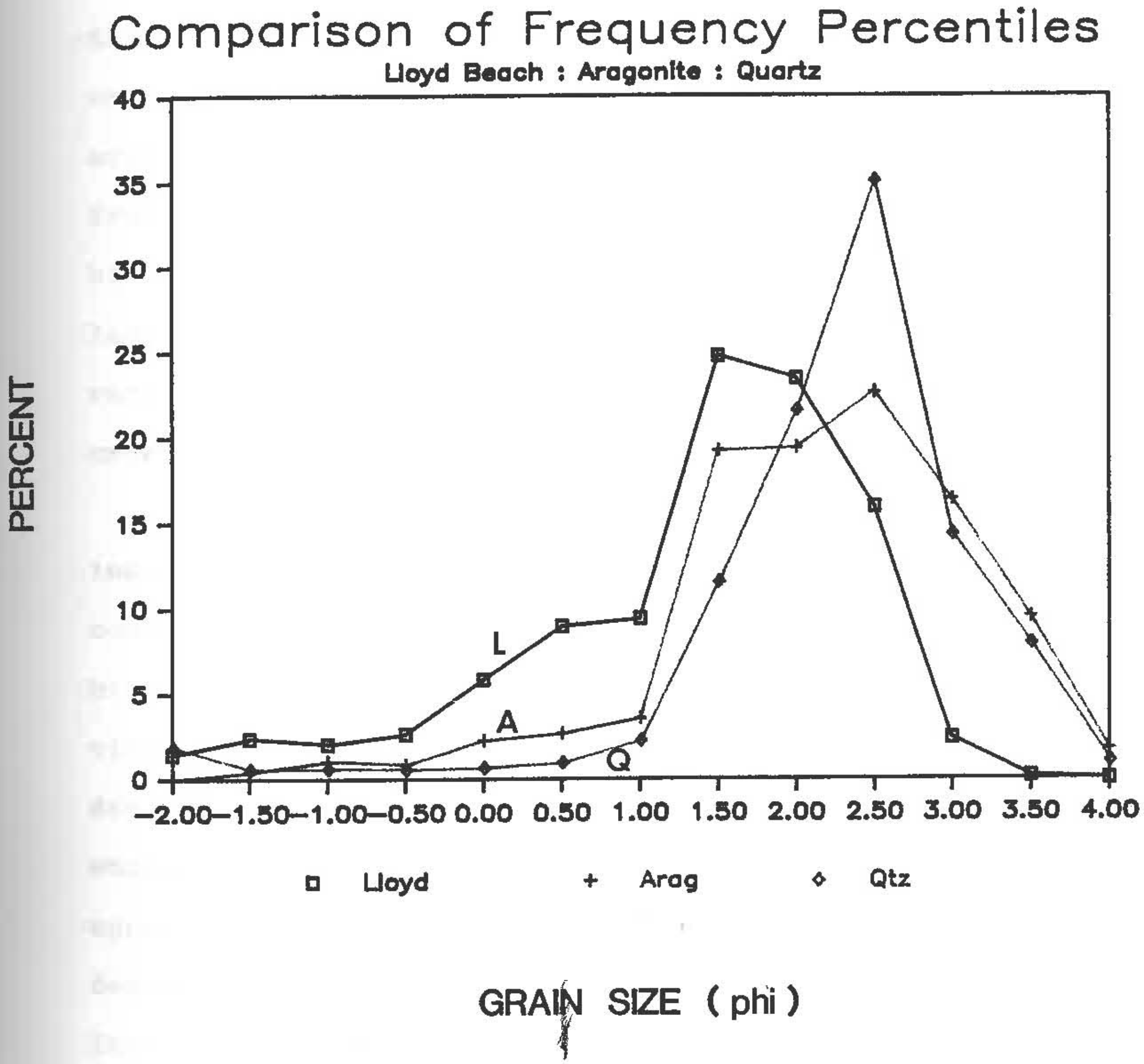
Kurtosis quantitatively measures the ratio between the sorting in the tails of the curve and the sorting in the central portion. If the central portion is better sorted than the tails, the curve is said to be excessively peaked or leptokurtic. If the tails are better sorted than the central portion, the curve is flat-peaked or platykurtic. According to Folk (1968) the following are the calculated values for the test materials:

Lloyd Beach	1.093	normal or mesokurtic
Aragonite	1.132	leptokurtic (slightly peaked)
Quartz	1.710	very leptokurtic (very peaked)

Figure 15 is a line plot of the weight frequencies in each size class. It illustrates the variation in skewness and kurtosis between the three test materials quite distinctively. See Appendix A for associated datum.

Figure 15

Frequency percent comparison between aragonite, quartz, and Lloyd Beach


Comparison of Frequency Percentiles
Lloyd Beach : Aragonite : Quartz
PERCENT
40
35
30
25
20
15
10
5
0
L
A
Q
−2.00
−1.50
−1.00
−0.50
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
□ Lloyd
+ Arag
◇ Qtz
GRAIN SIZE (phi)

Composition

One of primary reasons for comparing the transport of a quartz and aragonite beach sand is because of their difference in bulk composition. The results of calcium carbonate dissolution experiments indicate that the aragonite sand is nearly 100% calcium carbonate ranging from a pure oolitic chemical precipitate to a fragmented, biogenic coralline and molluscan shell matrix. This is largely the result of the physical and chemical variability in the in situ environment during crystallization and reworking.

The quartz sand was much different. Dissolution indicated 90-93% quartz content. The remaining volume was comprised mostly of fragmented and well preserved marine bivalve shells. From a compositional and textural point of view this material is rather enigmatic. Most of present day Florida beaches consist of no more than 25-30% quartz whose original source locality was in the Appalachians approximately 800 kilometers to the north. During deposition, conditions must have been favorable for increased erosion and transport of quartz down the southeast Florida coast. The quarry from which this material was removed is on a north-south structural high representing a series of former interglacial beach advances (Dr. A.K. Craig, pers.com.). The very well sorted, homogeneous nature of the quartz suggests that it was a

TABLE 6

% CALCIUM CARBONATE DATA

Lloyd Park Beach

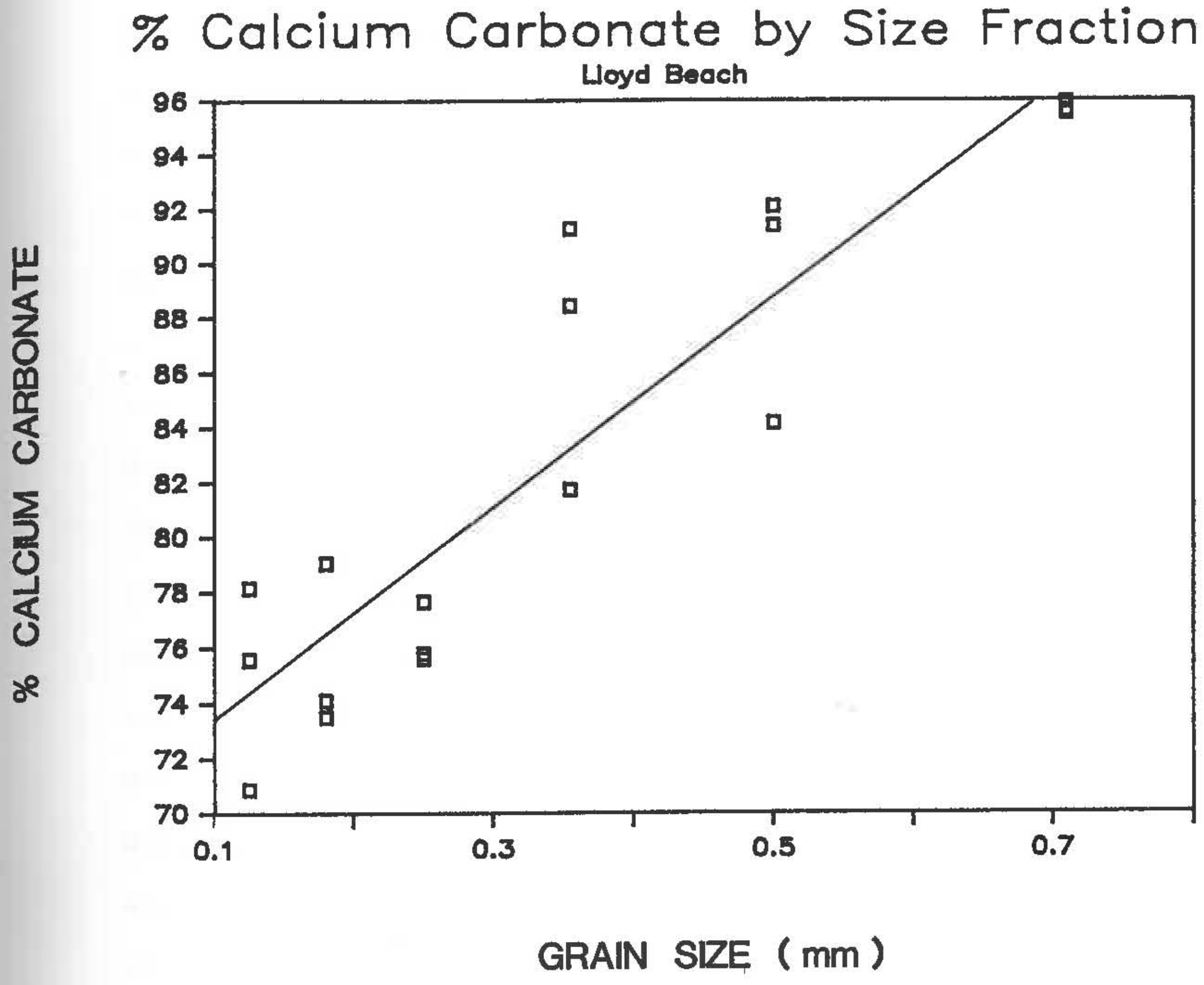
Fraction	%$CaCO_3$	%Qtz	Mean % $CaCO_3$	Mean % Qtz
0.71mm	95.91	4.09		
(0.5 phi)	95.59	4.41	95.67	4.33
	95.51	4.49		
0.50mm	84.14	15.86		
(1.0 phi)	92.10	7.90	89.21	10.79
	91.39	8.61		
0.355mm	81.73	18.27		
(1.5 phi)	88.43	11.57	87.15	12.85
	91.28	8.72		
0.250mm	77.65	22.35		
(2.0 phi)	75.62	24.38	76.36	23.64
	75.80	24.20		
0.180mm	73.50	26.50		
(2.5 phi)	79.06	20.94	75.55	24.45
	74.10	25.90		
0.125mm	78.17	21.82		
(3.0 phi)	70.87	29.13	74.88	25.12
	75.59	24.41		
Bulk	87.79	12.21		
	86.54	13.46	87.21	12.79
	87.29	12.71		

Quartz

Bulk	6.32	93.68		
	5.54	94.46		
	5.66	94.34	6.82	93.18
	9.78	90.22		

Figure 16

Percent calcium carbonate
contained on Lloyd Beach


% Calcium Carbonate by Size Fraction
Lloyd Beach
% CALCIUM CARBONATE
96
94
92
90
88
86
84
82
80
78
76
74
72
70
0.1
0.3
0.5
0.7
GRAIN SIZE (mm)

highly reworked beach sand and yet this is contradicted by its very angular appearance.

Table 6 summarizes the compositional variability of the quartz and Lloyd Beach sands. Samples taken from Lloyd Park beach were tan to gray biogenic calcium carbonate fragments (molluscan and coralline) with lesser amounts of fine-grained quartz. There is a positive correlation between the percent calcium carbonate present and increasing grain size. As the size of the material increases from 0.125mm, the percent calcium carbonate increases from approximately 75% to nearly 100% (Figure 16). Although the correlation coefficient is 0.91, it is difficult to assign a specific hydrodynamic cause for this selective sorting since the larger quartz grain sizes may or may not have been present in equal or unequal volumes during the 1976 renourishment. It may be possible that under a given set of wave conditions on Lloyd Park beach, a hydraulic equivalence exists between the larger biogenic calcium carbonate grains and the smaller quartz grains allowing them to coexist in dynamic equilibrium. A bulk composition analysis of Lloyd Beach yielded approximately 87% calcium carbonate, 12% quartz, and a very small (< 1%) heavy mineral content.

Density

A series of bulk density tests were performed on the aragonite, quartz, and Lloyd Beach samples to estimate the

TABLE 7

DENSITY DETERMINATIONS

Type	Sample Size (grams)	Density (g/cm3)	Mean Density (g/cm3)
Lloyd Beach	35.67	2.702	
	49.46	2.695	2.70
	33.79	2.703	
Aragonite	25.42	2.733	
	35.00	2.724	2.73
	39.92	2.734	
Quartz	36.08	2.643	
	32.93	2.677	2.65
	33.56	2.642	

average density of these materials within all of the grain size classes. As expected, the quartz had the lowest value and aragonite the highest. The Lloyd Beach sand is a mixture of calcite, quartz, and aragonitic shells and therefore shows a density intermediate between the quartz and aragonite samples. Table 7 shows the results of the density determinations.

Laboratory results on the mean grain size fraction of the aragonite (0.27mm) showed a density of approximately 2.85 g/cm3, which is considerably higher than the value obtained from the bulk sample (2.73 g/cm3). Additional aragonite experiments indicated a density differentiation according to grain size with density decreasing as grain size increases. This density variability probably reflects the complex relationship between the number of oolitic lamellae per grain with respect to the grain's original nucleus size.

Grain Shape Analysis

Shape is a complex property of a grain and has generally been distinguished by sedimentologists (Blatt et al.,1980) into four main aspects: surface texture, roundness, sphericity, and form. I examined roundness and sphericity to correlate these properties with relative transport rates. Roundness refers to the sharpness of the corners and edges of the grain. Sphericity measures the degree to which the grain approaches a spherical shape.

The most universally accepted definitions of these properties are given by Wadell (1932): roundness is the ratio of the average radius of curvature of the corners to the radius of the largest inscribed circle; sphericity is the ratio between the diameter of the sphere with the same volume as the particle and the diameter of the circumscribed sphere.

Although sophisticated measurement techniques exist (such as Fourier analysis of lower and higher order shape harmonics) the most commonly used method is by visual comparison to standardized images. Although this technique has low accuracy and poor reproducibility, it is simple, common in routine field and laboratory investigations (Griffiths, 1967), and compatible with the two dimensional images observed under a microscope. For the purposes of relative comparisons in this study it is believed to be a suitable procedure.

Two roundness scales were used to compare aragonite, quartz, and Lloyd Beach samples. The first is based on images by Powers (1953) whose coefficients were later numerically log-transformed by Folk (1972). Six classes are described from 0 (perfectly angular) to 6 (perfectly rounded). The second roundness scale compared images generated by Krumbein (1941) with associated numerical coefficients from 0.1 (most angular) to 0.9 (most rounded). Only one scale was used to compare sphericity between the test materials based on images by Rittenhouse (1943). The numerical coefficients range from 0.45 (ellipsoidal) to 0.97 (perfect spheres). Table 8 summarizes the results of these three techniques. According to the Powers scale, roundness of the three samples would be classified as:

Quartz:	subangular
Aragonite:	well-rounded
Lloyd Beach:	subangular to subrounded

The sphericity results can be classified as aragonite being quite spherical with the quartz and Lloyd Beach materials moderately spherical.

The micro-photographs in Figure 17 to 27 show the shape variations within each grain size class for all three materials. There appear to be several patterns for the quartz, aragonite, and Lloyd Beach sand. The quartz became slightly more angular with decreasing grain size showing almost no calcium carbonate present below 2.0 phi (0.250mm). This may be significant since the mode of the quartz frequency distribution is 2.5 phi (0.180mm), a size smaller than the 2.0 phi cutoff. As the aragonite particle size decreases, the grains go from a cemented biogenic nature to predominantly well rounded oolites. Such a trend would account for aragonite's dramatic numerical decrease in roundness and sphericity observed between 0.5 phi (0.71mm) and 1.0 phi (0.50mm) in Table 8. Finally,

Aragonite

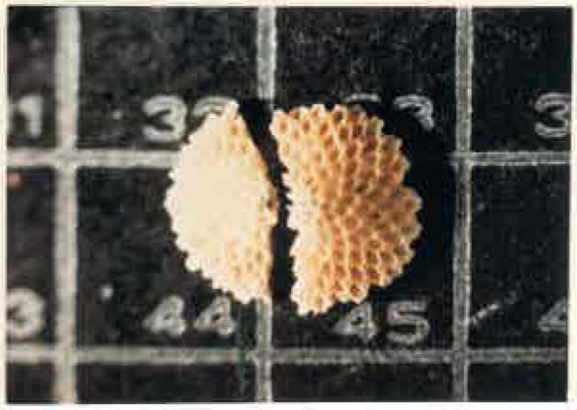
Figure 17

Microphotograph comparison of
the 2.80 mm size fraction of
aragonite, quartz, and
Lloyd Beach

Quartz

Lloyd Beach


18
20
32


44
45

Aragonite

Figure 18

Microphotograph comparison of
the 2.00mm size fraction of
aragonite, quartz, and
Lloyd Beach

Quartz

Lloyd Beach

Aragonite

Figure 19

Microphotograph comparison of the 1.40mm size fraction of aragonite, quartz, and Lloyd Beach

Quartz

Lloyd Beach


5
6
7
17


8
30


18
20
32

Aragonite

Figure 20

Microphotograph comparison of
the 1.00mm size fraction of
aragonite, quartz, and
Lloyd Beach

Quartz

Lloyd Beach


17
28
21
42
43

Aragonite

Figure 21

Microphotograph comparison of
the 0.71mm size fraction of
aragonite, quartz, and
Lloyd Beach

Quartz

Lloyd Beach


30
32
42
43
44
31
33
43
44
45
19
20
2

Aragonite

Figure 22

Microphotograph comparison of
the 0.50mm size fraction of
aragonite, quartz, and
Lloyd Beach

Quartz

Lloyd Beach


17
18
19
29
30
31
15
16
17
27
14
15
16
26
27

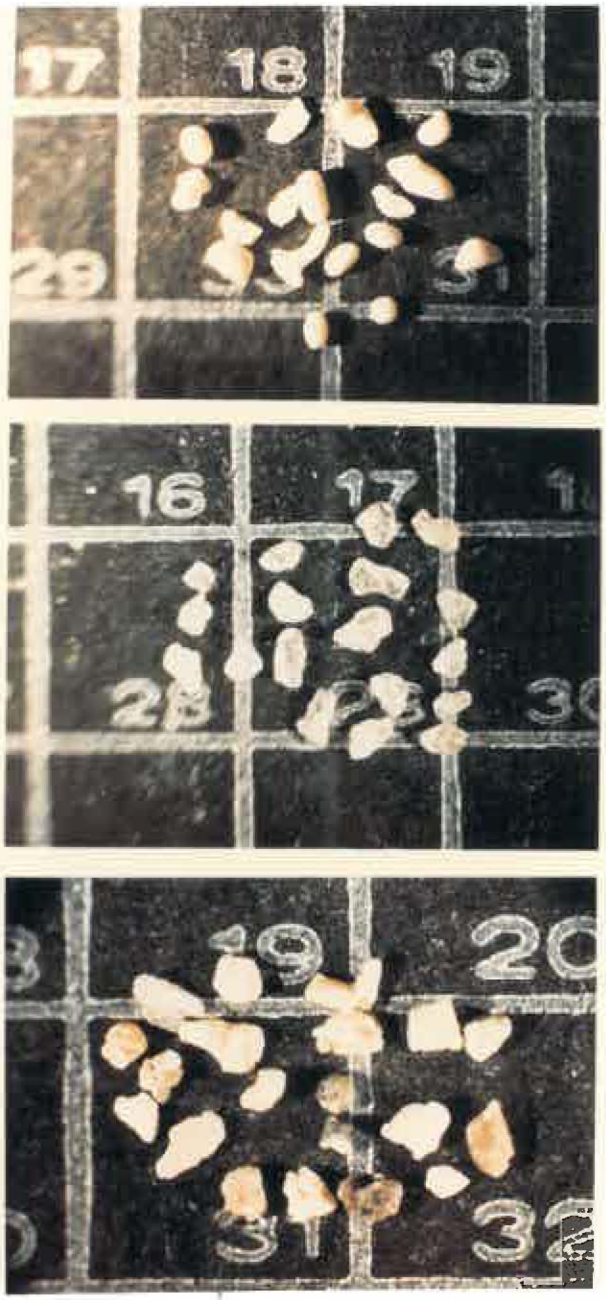
Aragonite

Figure 23

Microphotograph comparison of the 0.35mm size fraction of aragonite, quartz, and Lloyd Beach

Quartz

Lloyd Beach


17
18
19
29
31
16
17
28
30
19
20
31
3

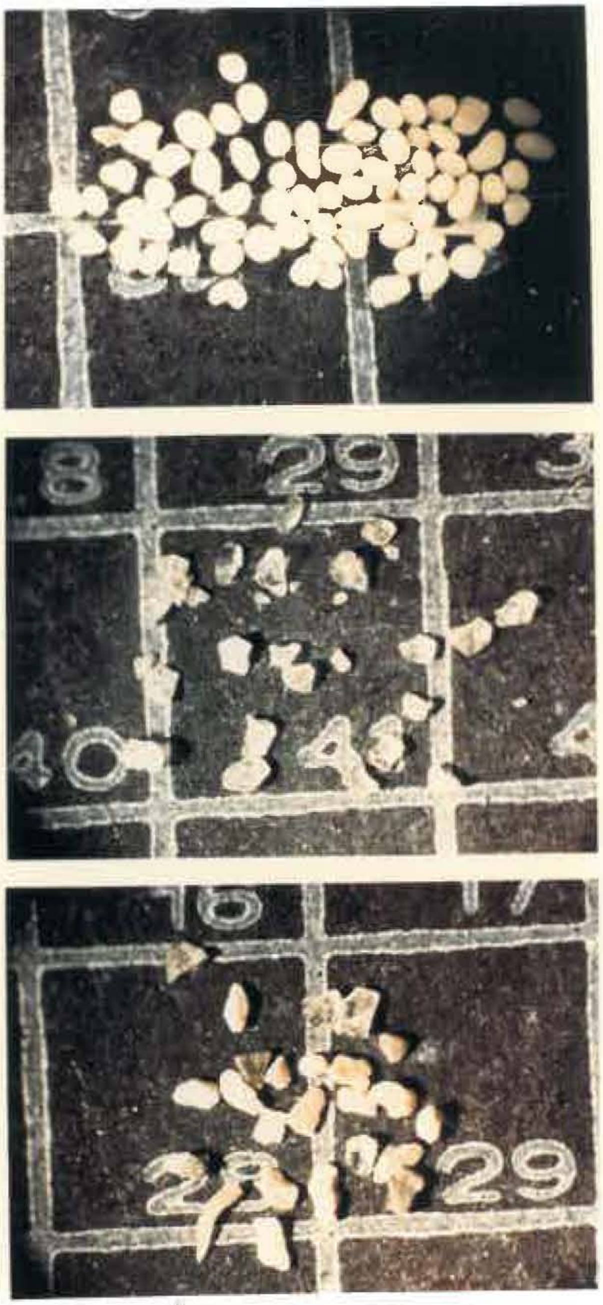
Aragonite

Figure 24

Microphotograph comparison of the 0.25mm size fraction of aragonite, quartz, and Lloyd Beach

Quartz

Lloyd Beach


8
29
40
41
16
28
29

Aragonite

Figure 25

Microphotograph comparison of
the 0.18mm size fraction of
aragonite, quartz, and
Lloyd Beach

Quartz

Lloyd Beach


30
31
43
16
7
28
16
7
28

Aragonite

Figure 26

Microphotograph comparison of the 0.125mm size fraction of aragonite, quartz, and Lloyd Beach

Quartz

Lloyd Beach


15
16
27
28
32
33

Figure 27

Microphotograph illustrating the aragonite 0.09mm size fraction

TABLE 8

ROUNDNESS AND SPHERICITY

Based on
Coefficients of: Powers (1953) for Roundness
Krumbein (1941) for Roundness
Rittenhouse (1943) for Sphericity

Average for all size fractions:

Type	Powers Mean (Stdev)	Rittenhouse Mean (Stdev)	Krumbein Mean (Stdev)
Quartz	1.8 (0.75)	0.73 (0.06)	0.48 (0.12)
Aragonite	4.5 (1.86)	0.84 (0.08)	0.72 (0.20)
Lloyd Beach	2.3 (0.64)	0.71 (0.04)	0.48 (0.10)

Average based on mean size of each material:

Quartz	1.0	0.69	0.30
Aragonite	6.0	0.94	0.90
Lloyd Beach	2.0	0.75	0.50

TABLE 9

SUMMATION OF THE PHYSICAL CHARACTERISICS OF ARAGONITE, QUARTZ, AND LLOYD BEACH

Factor	Aragonite	Quartz	Lloyd Beach
Mean Size	0.27mm	0.25mm	0.43mm
Sorting	Well Sorted	Well Sorted	Moderately Sorted
Skewness	Near Symmetric	Coarse Skewed	Very Coarse Skewed
Kurtosis	Slightly Peaked (leptokurtic)	Very Peaked (leptokurtic)	Normal (mesokurtic)
Composition	Calcium Carbonate	93% Quartz 7% CaCO3	87% CaCO3 13% Quartz
Density	2.73 g/cm3	2.65 g/cm3	2.70 g/cm3
Roundness	Well Rounded	Subangular	Subangular to Subrounded
Sphericity	Very Spherical	Moderately Spherical	Moderately Spherical

there is a slight difference in roundness within the Lloyd Beach sand between the quartz and calcium carbonate components in each size fraction. The quartz component always is more rounded, probably due to the constant reworking associated with the great distance it has been transported from its source area in the Appalachians.

Table 9 compares and contrasts the physical characteristics of the Lloyd Beach, aragonite, and quartz test materials.

III. METHODS

Tracer Preparation

There are numerous techniques available for preparing sediment tracer compounds. A complete list of commercial manufacturers, paints, resins, binding agents, coating thickness specifications, and overall performance standards can be found in Yasso (1962) and Ingle (1966). Desirable properties that should result from the applied technique include:

1) The coating should have a minimal and uniform thickness.
2) It should possess a rapid drying rate for quick introduction into the experiment.
3) Over short time periods it should not fade or lose its fluorescent property.
4) It should have little or no solubility in fresh or saline water and resist short term abrasion losses.

The staining method applied in this study was based on communications with the Coastal Engineering Laboratory, Dept. of Coastal & Oceanographic Engineering, at the University of Florida where similar materials have been prepared for large commercial projects. The selected fluorescent dye was a melanine copolymer resin produced by the Day-Glo Color Corporation which was mixed with dry powdered milk and water in the following proportions:

Per 45 kilograms of sand:

2.2 kilograms of water
1 kilogram of dye
0.91 kilograms dry powdered milk

For studies lasting longer then three to four days, the dry powdered milk should be replaced by a hardener and binding agent.

After uniform introduction of the dye slurry to each 45 kilogram sample, sand was oven baked for approximately two hours at 350 degrees farenheit with periodically stirring to prevent excessive cohesion. The resulting material could plainly be identified under a microscope in white or ultraviolet light.

Experiment 1 - Design

The first of two sediment transport experiments took place on September 5, 1986 in John U. Lloyd Beach State Recreational Area in a grid located approximately 450 meters south of Port Everglades Inlet. At mean low tide (3:47 pm), 45 kilograms each of fluorescent aragonite, quartz, and Lloyd Beach sand (dyed different colors and mixed together) were placed on the beach in a line 3 meters long and 1.2 meters wide of uniform thickness oriented perpendicular to the shoreline. The seaward end of the injection line began two meters above the low tide line. Over the duration of the experiment, a mixed wind and wave pattern was observed. For the first two hours after tracer addition there was a slight northerly breeze (< 8 kph) which changed to a 8 kph southeasterly wind for the remainder of the experiment. This resulted in a net northerly littoral drift for the entire experiment. The wave conditions were characterized by calm, spilling

Figure 28

Experiment 1 - transect design

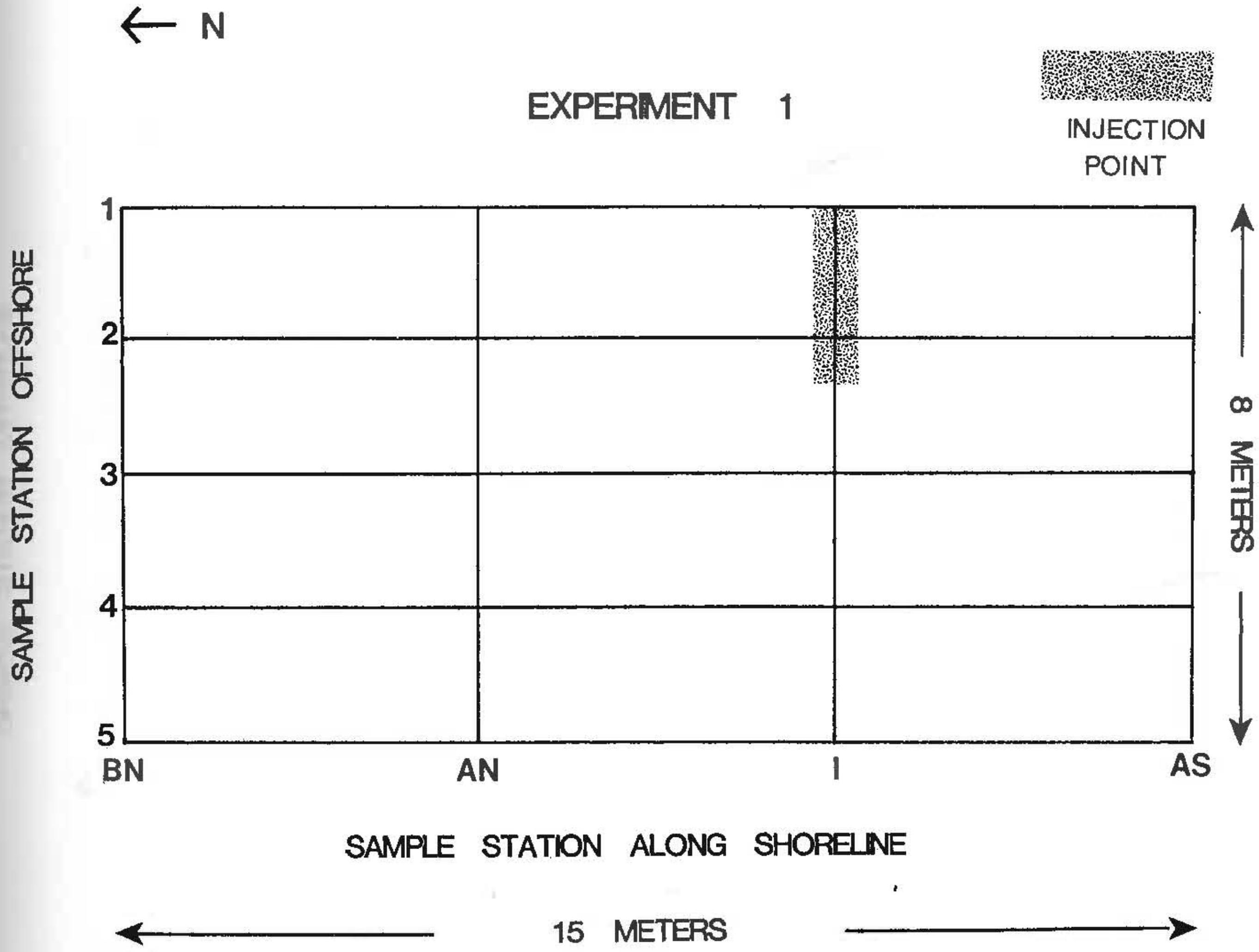

N
EXPERIMENT 1
INJECTION POINT
SAMPLE STATION OFFSHORE
1
2
3
4
5
BN
AN
I
AS
8 METERS
SAMPLE STATION ALONG SHORELINE
15 METERS

Figure 29

Experiment 2 - transect design

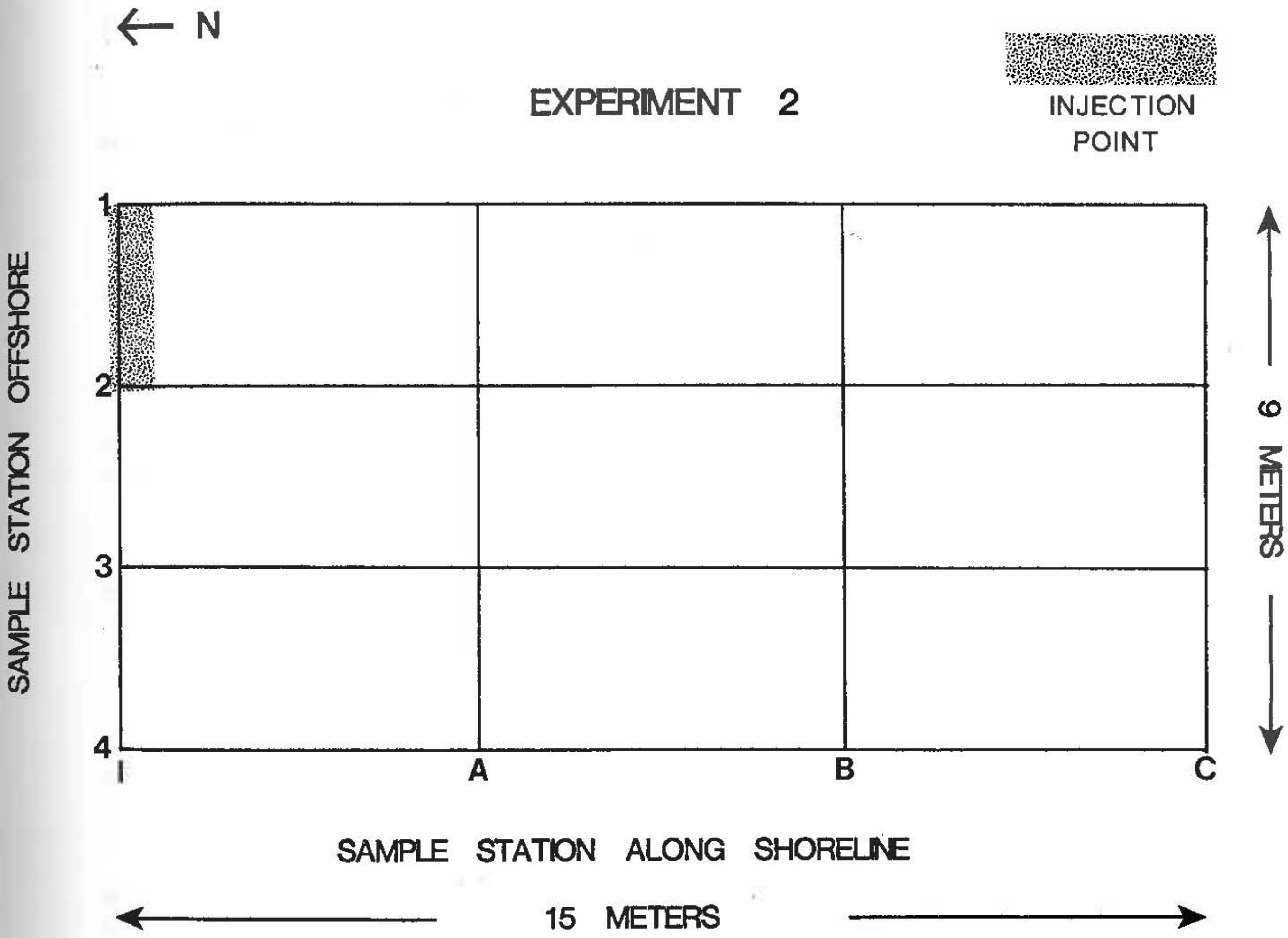

N
EXPERIMENT 2
INJECTION POINT
SAMPLE STATION OFFSHORE
1
2
3
4
I
A
B
C
9 METERS
SAMPLE STATION ALONG SHORELINE
15 METERS

TABLE 10

COMPARISON BETWEEN THE NEARSHORE CONDITIONS IN EXPERIMENTS 1 AND 2

Factor	Experiment 1	Experiment 2
Wind	< 5 mph from east to southeast	5-10 mph from northeast
Waves	3.5 second period "spilling"	4.0 second period "surging to plunging"
Wave Angle of Approach	10 degrees from south	30-35 degrees from north
Beach Slope	1 / 8	1 / 8
Wave Height at Breaking (Hb)	0.56 meters (1.85 feet)	1.05 meters (3.46 feet)
Water Depth at Breaking (Db)	0.46 meters (1.5 feet)	0.91 meters (3.0 feet)

breakers with a 3.5 second period approaching the shoreline at a very small angle, nearly perpendicular. Due to these circumstances, the net sediment transport distances were small and the sampling interval was narrowed in accordance with these conditions (Figure 28). After six hours of reworking in the surf zone (high tide), a total of 20 samples were removed from a 120 square meter area using a PVC coring device 5 cm long by 3.8 cm in diameter. Approximately 800 grams (dry weight) of sand per station were extracted from the top five centimeters of bed load material at each sampling location for further analysis.

Experiment 2 - Design

The second experiment in John U. Lloyd Beach State Recreational Area was performed on September 12, 1986 approximately 450-500 meters south of Port Everglades Inlet in the intertidal zone. Equal masses (45 kilograms) of aragonite, quartz, and Lloyd Beach sand were introduced at mean low tide (9:28 am). The injection line, 3.3 meters long and 1 meter wide, was positioned similarly to experiment 1 on the beach face (inherent slope was 1 on 8). Core samples were extracted at high tide from a grid downdrift of the injection line after six hours of wave action.

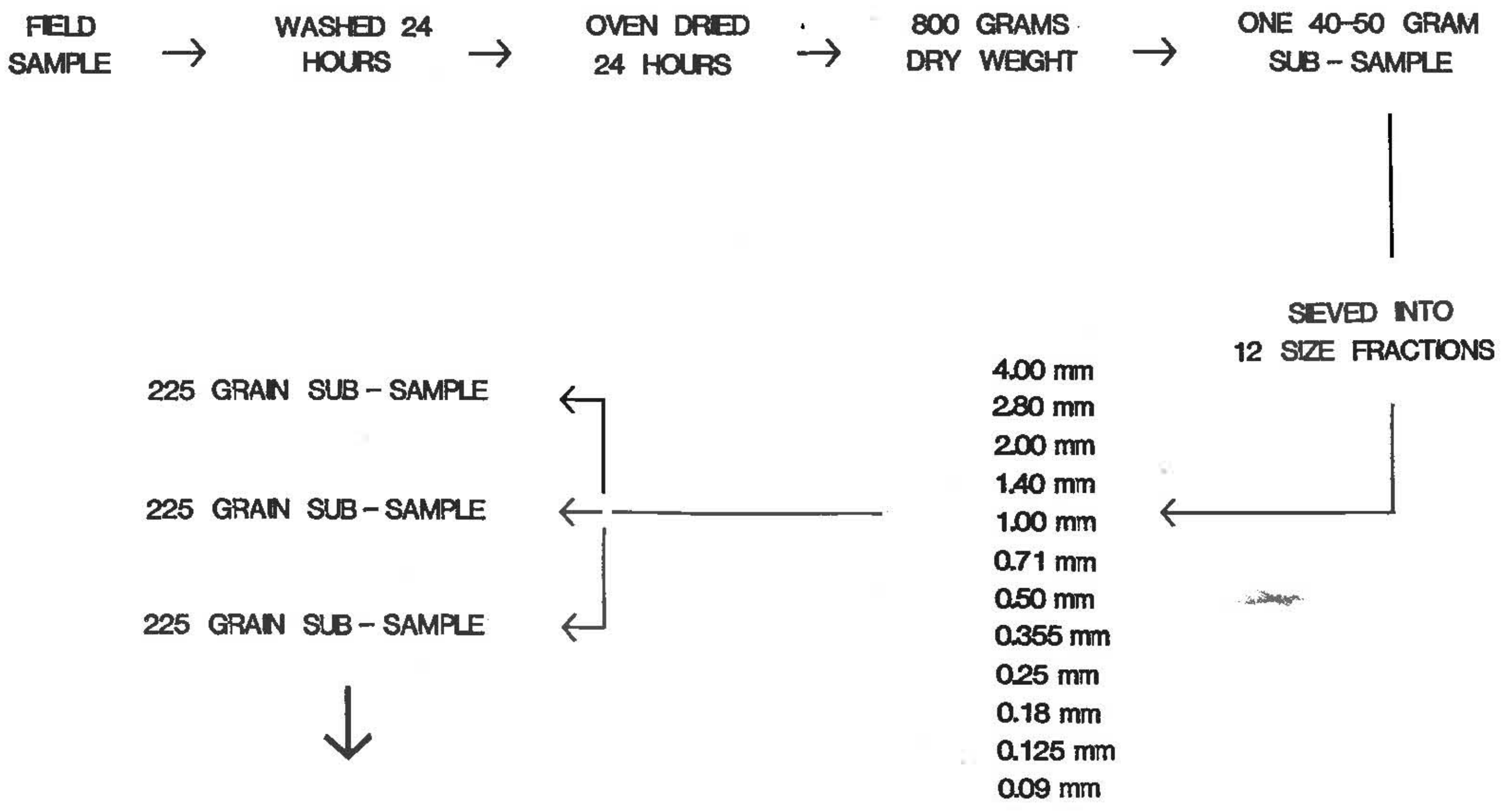
The nearshore wind and wave conditions were considerably different than in experiment 1. The winds gusted at 8-15 kph from the northeast inducing surging and plunging waves with a 4.0 second period. The wave angle of approach (30 degrees) was substantially greater, and coupled with the higher wind conditions, caused an increased net longshore component of sediment movement. The entire direction of transport in the second experiment was to the south and the sampling transects were positioned accordingly (Figure 29). At the conclusion of the experiment (high tide), 16 samples (800 grams each) were removed from a 135 square meter area of the intertidal zone for further laboratory processing. Table 10 compares and summarizes the physical conditions during experiments 1 and 2.

Laboratory Analysis

Figure 30 is a schematic diagram showing how the sediment core samples were processed to obtain the raw transport data. After washing, oven drying, and splitting, each sample was sieved into 12 size fractions. To quantify the net relative sediment transport within the experimental grid area, triplicate sub-samples (225 grains per sample) from each grain size fraction were examined under a microscope. Results were reported as the percent tracer aragonite, quartz, and Lloyd Beach sand present at each station. An average percent tracer value for each grain fraction at its respective location in the transect was then tabulated.

Figure 30

Procedure to obtain the sediment transport data from the field



% TRACER SAND = AVG # TRACER GRAINS / 225 SAMPLE

IV. RESULTS

Littoral Transport of Bulk Materials

In the initial analysis, the movement of the entire 135 kilograms of tracer sand in both experiments was examined to delineate the direction and relative magnitude of transport in the intertidal zone. The goal was to compare how equal masses of quartz and aragonite (45 kilograms each) react under wave attack without regard to their respective grain size distributions. The rationale was that by evaluating the relative transport behavior of aragonite and quartz using equal masses, their behavior as beach renourishment materials could be simulated in John U. Lloyd Beach State Recreational Area.

Within each sampling grid, sediment movement was assessed in two directions: longshore parallel to the beach, and onshore-offshore perpendicular to the beach. In both cases it was felt that the best indication of the relative movement between the quartz and aragonite could be achieved by examining the net transport along individual lines in the grid and then further refining these into total net longshore and net onshore-offshore movement for the entire grid.

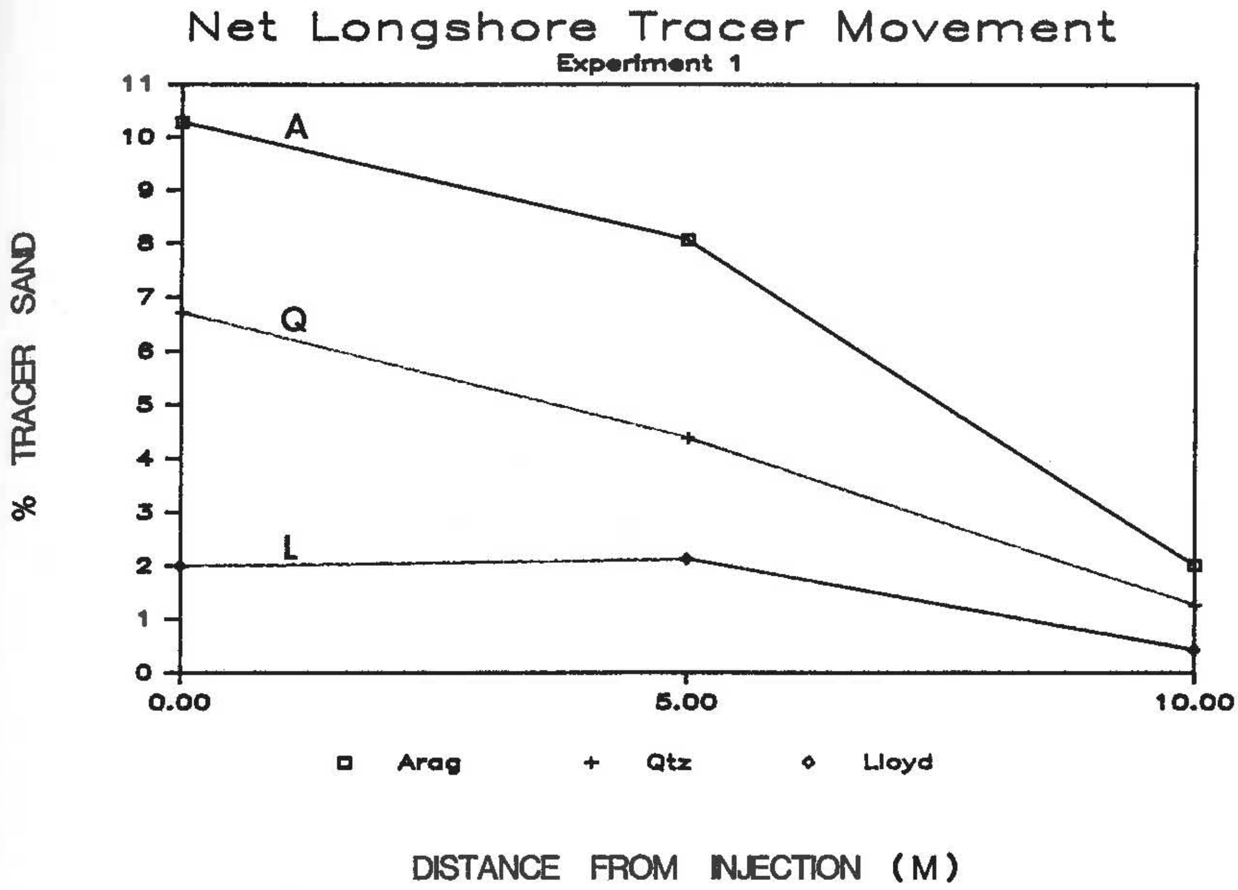
Figures 31 through 50, (based on microscopic grain counts) graphically display the percent tracer of aragonite, quartz, and Lloyd Beach sand remaining at particular areas in the grid upon completion of experiments

Figure 31

Net longshore tracer movement in experiment 1

Figure 32

Net onshore-offshore tracer movement in experiment 1


Net Longshore Tracer Movement
Experiment 1
% TRACER SAND
0
1
2
3
4
5
6
7
8
9
10
11
A
Q
L
0.00
5.00
10.00
□ Arag
+ Qtz
◇ Lloyd
DISTANCE FROM INJECTION (M)

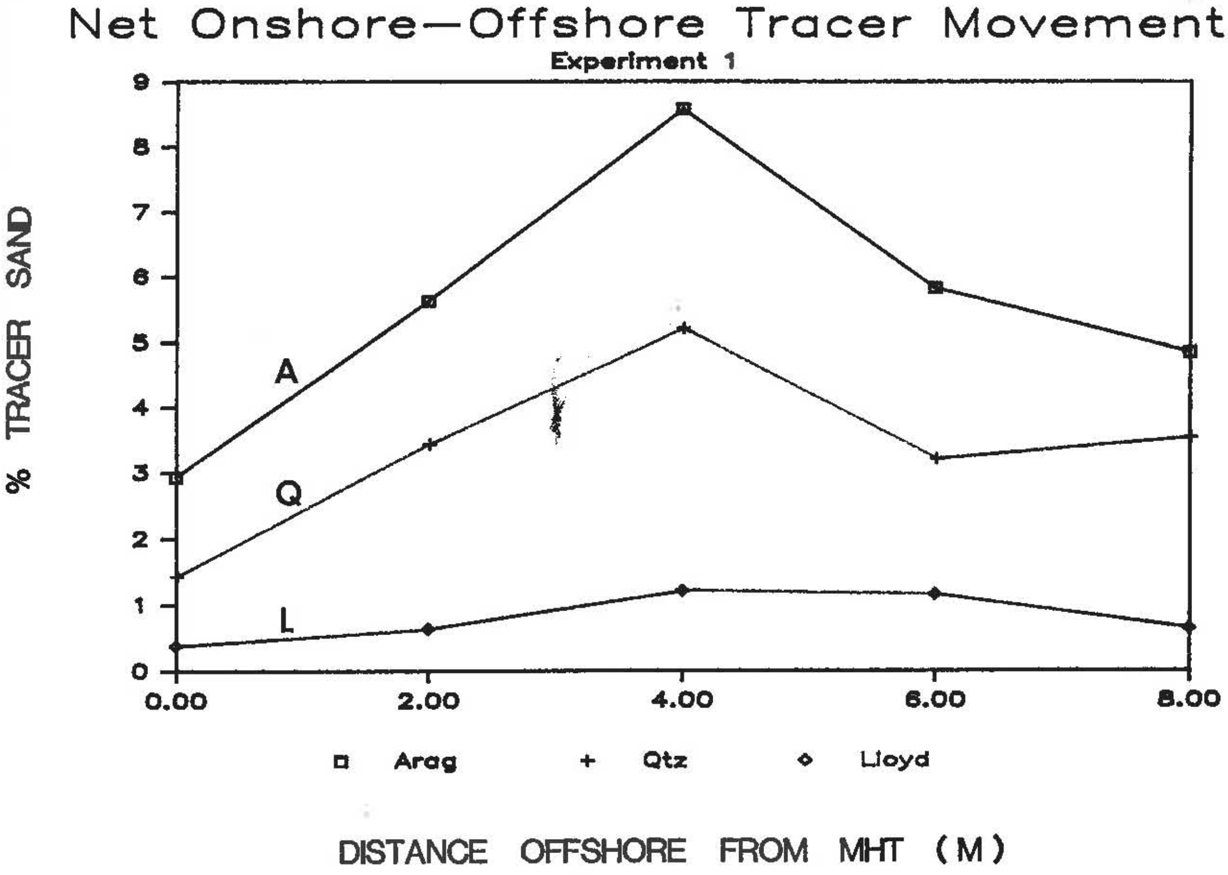
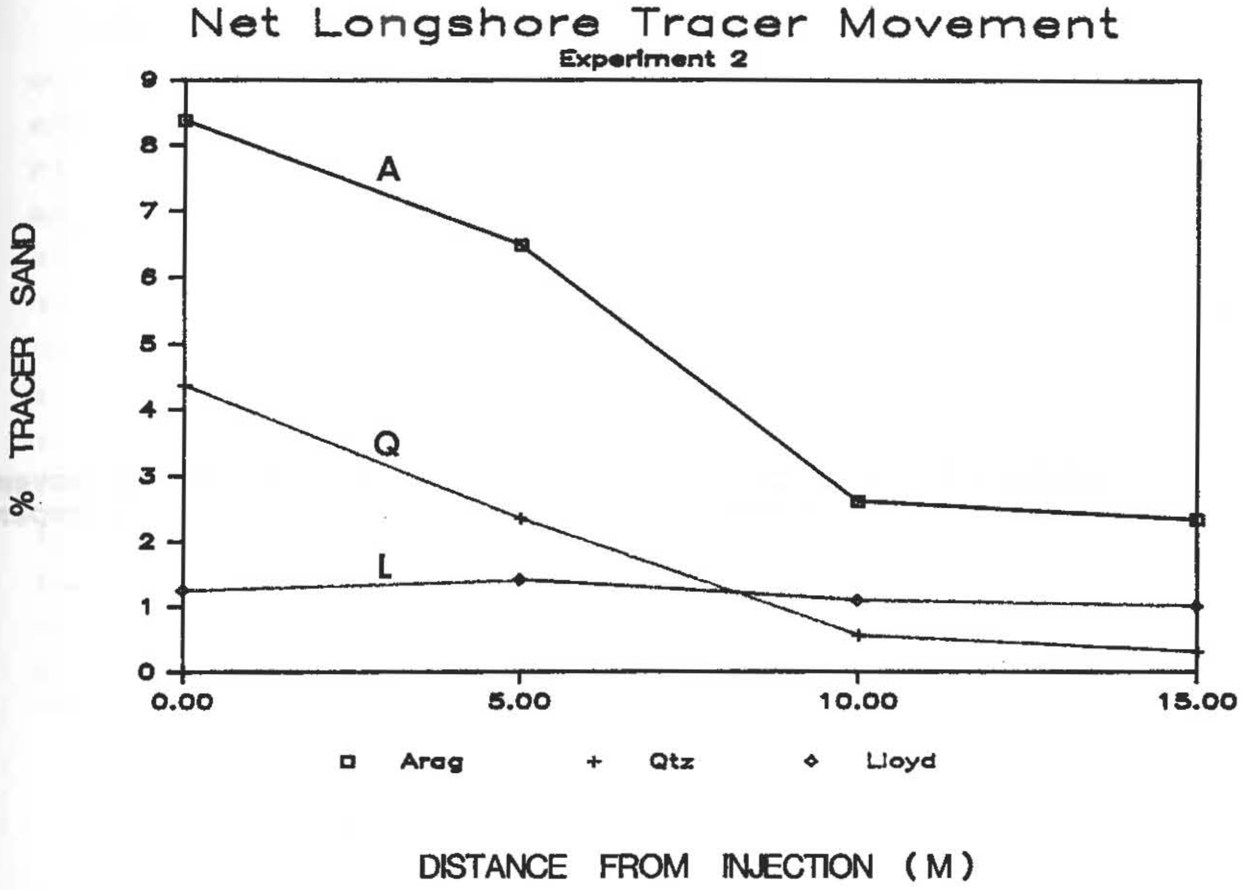

Net Onshore—Offshore Tracer Movement
Experiment 1
% TRACER SAND
0
1
2
3
4
5
6
7
8
9
A
Q
L
0.00
2.00
4.00
6.00
8.00
□ Arag
+ Qtz
◇ Lloyd
DISTANCE OFFSHORE FROM MHT (M)

Figure 33

Net longshore tracer movement in experiment 2

Figure 34

Net onshore-offshore tracer movement in experiment 2


Net Longshore Tracer Movement
Experiment 2
% TRACER SAND
0
1
2
3
4
5
6
7
8
9
0.00
5.00
10.00
15.00
A
Q
L
□ Arag
+ Qtz
◇ Lloyd
DISTANCE FROM INJECTION (M)

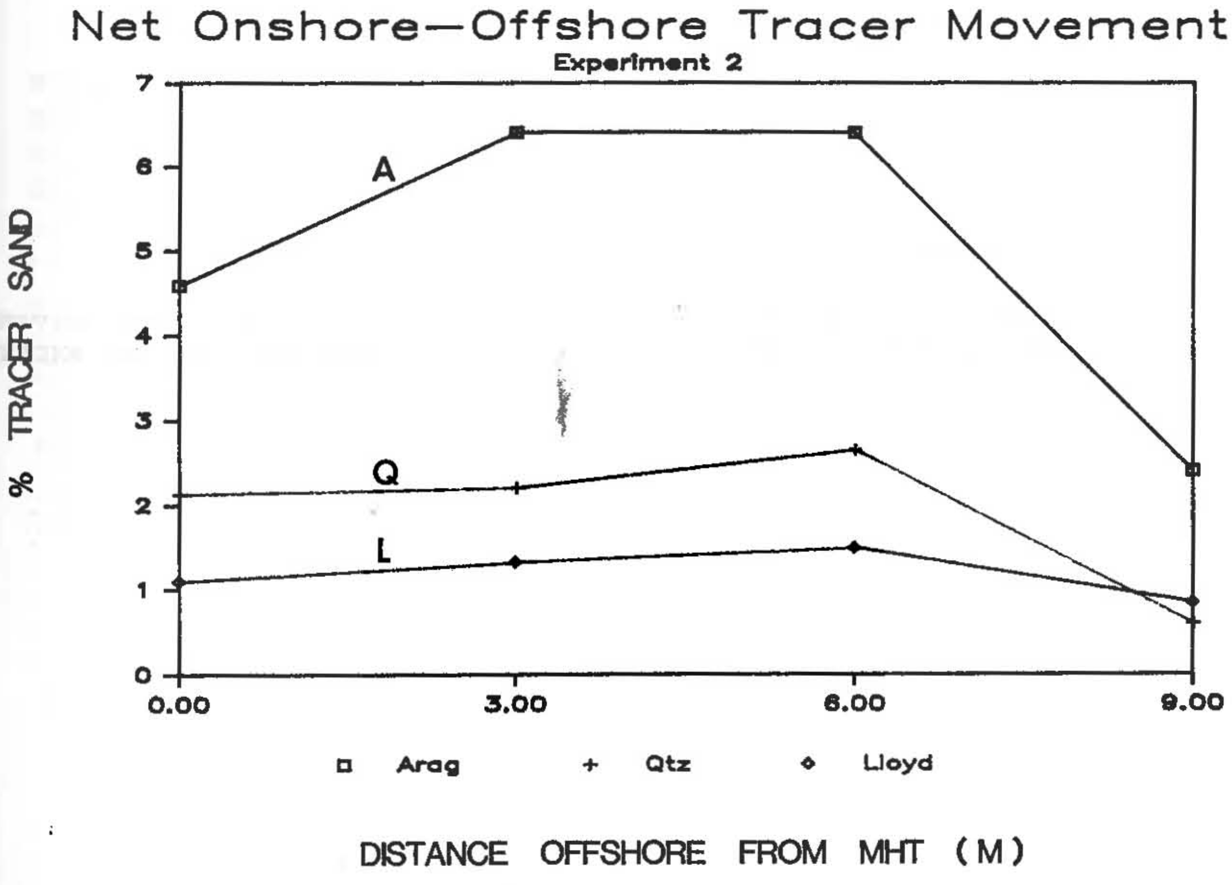

Net Onshore—Offshore Tracer Movement
Experiment 2
% TRACER SAND
0
1
2
3
4
5
6
7
0.00
3.00
6.00
9.00
A
Q
L
□ Arag
+ Qtz
◇ Lloyd
DISTANCE OFFSHORE FROM MHT (M)

Figure 35

Longshore tracer movement along line #1 in exper.1

Figure 36

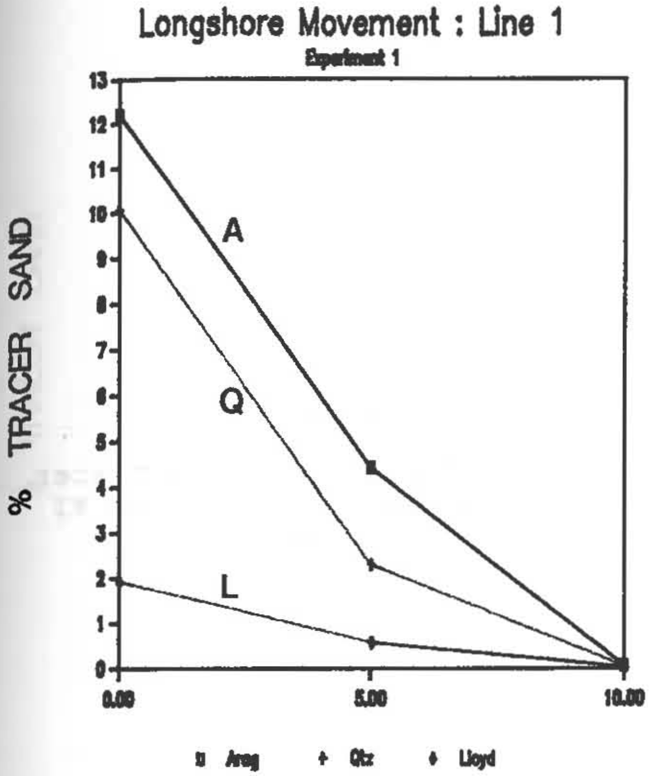
Longshore tracer movement along line #2 in exper.1

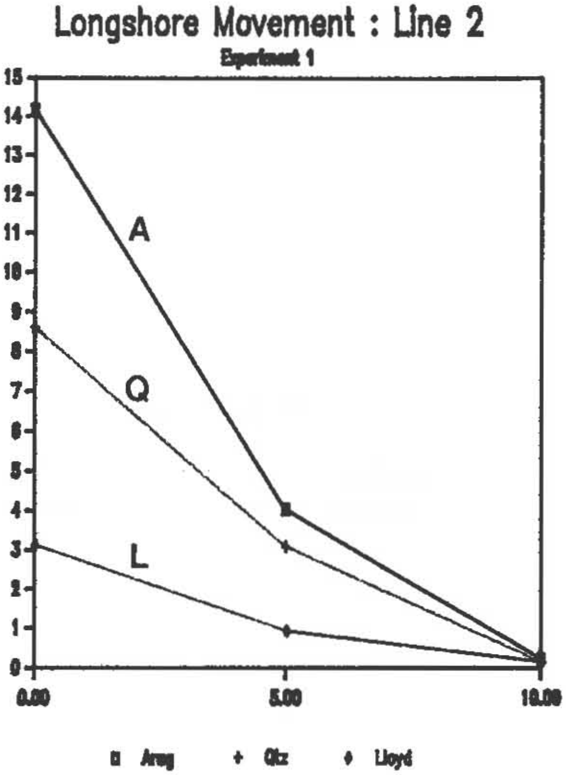
Figure 37

Longshore tracer movement along line #3 in exper.1

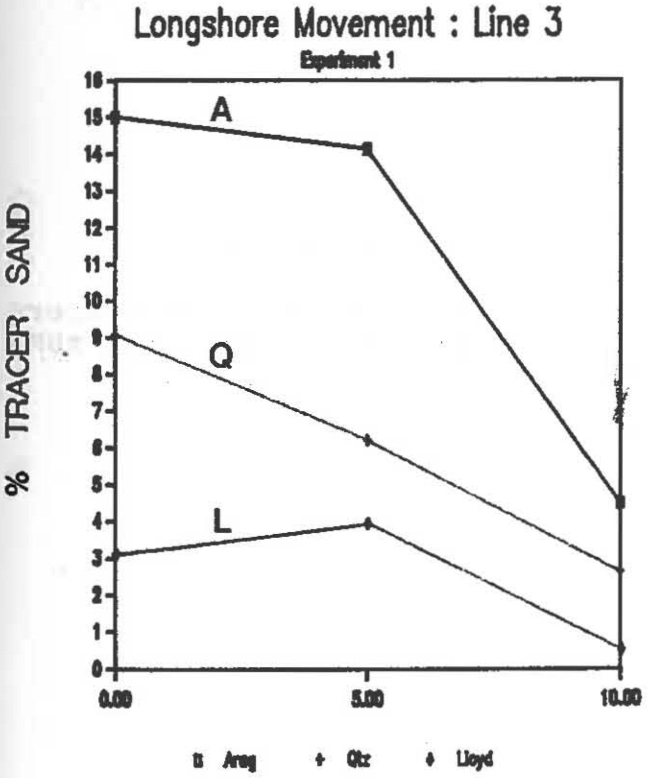
Figure 38

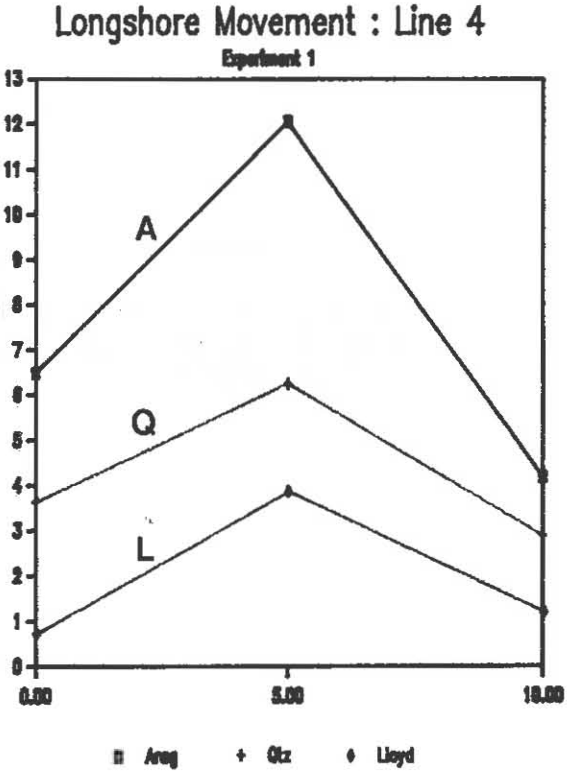
Longshore tracer movement along line #4 in exper.1


Longshore Movement : Line 1
Experiment 1
% TRACER SAND
13
12
11
10
9
8
7
6
5
4
3
2
1
0
A
Q
L
0.00
5.00
10.00
Arag
Qtz
Lloyd


Longshore Movement : Line 2
Experiment 1
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
A
Q
L
0.00
5.00
10.00
Arag
Qtz
Lloyd

DISTANCE FROM INJECTION (M)


Longshore Movement : Line 3
Experiment 1
% TRACER SAND
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
A
Q
L
0.00
5.00
10.00
Arag
Qtz
Lloyd


Longshore Movement : Line 4
Experiment 1
13
12
11
10
9
8
7
6
5
4
3
2
1
0
A
Q
L
0.00
5.00
10.00
Arag
Qtz
Lloyd

DISTANCE FROM INJECTION (M)

Figure 39

Longshore tracer movement along line #5 in exper.1

Figure 40

Onshore-offshore tracer movement along line #I in exper.1

Figure 41

Onshore-offshore tracer movement along line #AN in exper.1

Figure 42

Onshore-offshore tracer movement along line #BN in exper.1

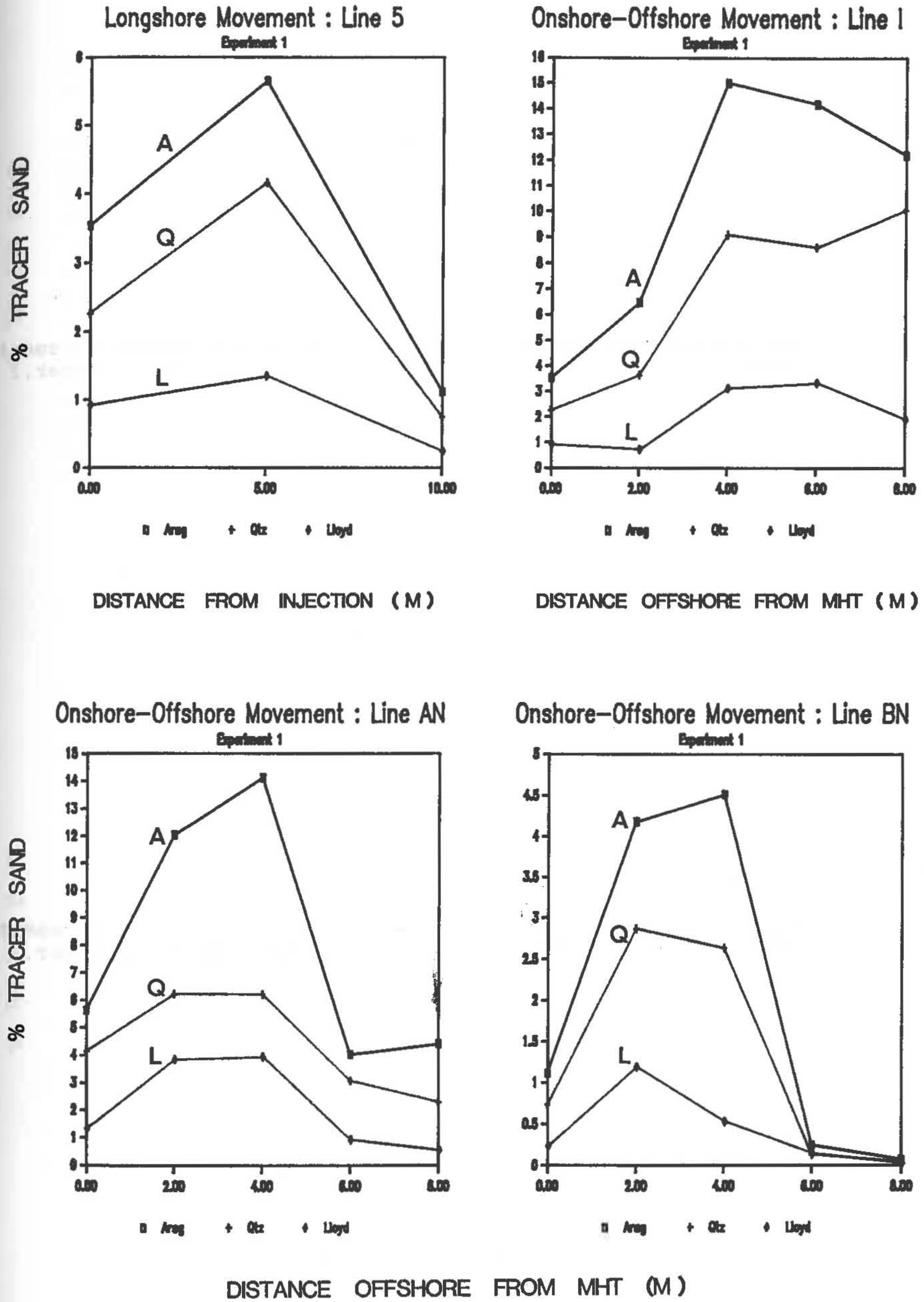

Longshore Movement : Line 5
Experiment 1
% TRACER SAND
0
1
2
3
4
5
6
A
Q
L
0.00
5.00
10.00
Arag
Qtz
Lloyd
DISTANCE FROM INJECTION (M)
Onshore-Offshore Movement : Line I
Experiment 1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
A
Q
L
0.00
2.00
4.00
6.00
8.00
Arag
Qtz
Lloyd
DISTANCE OFFSHORE FROM MHT (M)
Onshore-Offshore Movement : Line AN
Experiment 1
% TRACER SAND
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
A
Q
L
0.00
2.00
4.00
6.00
8.00
Arag
Qtz
Lloyd
Onshore-Offshore Movement : Line BN
Experiment 1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
A
Q
L
0.00
2.00
4.00
6.00
8.00
Arag
Qtz
Lloyd
DISTANCE OFFSHORE FROM MHT (M)

Figure 43

Longshore tracer movement
along line #1 in exper.2

Figure 44

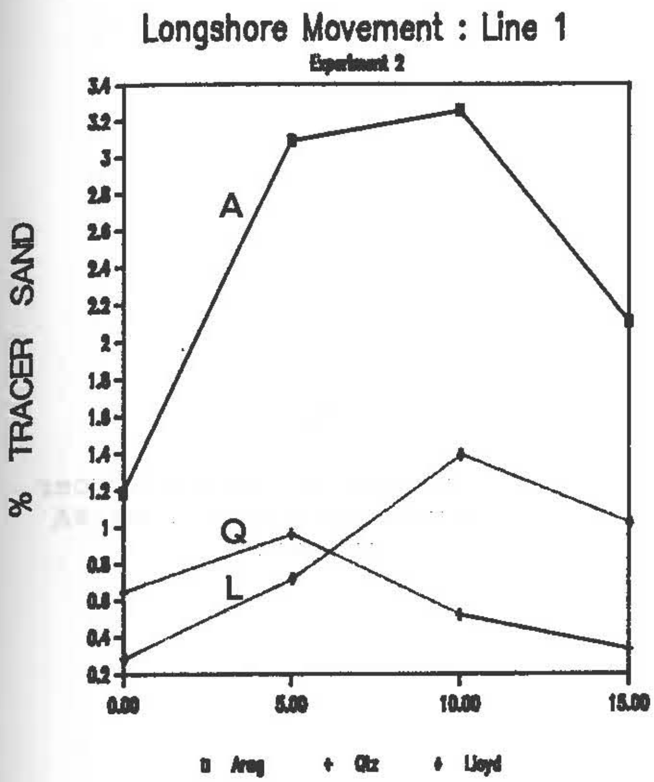
Longshore tracer movement
along line #2 in exper.2

Figure 45

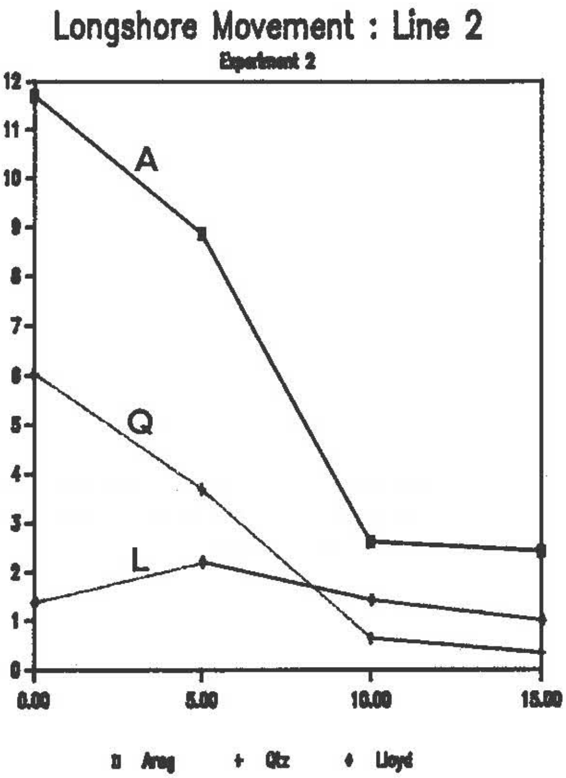
Longshore tracer movement
along line #3 in exper.2

Figure 46

Longshore tracer movement
along line #4 in exper.2

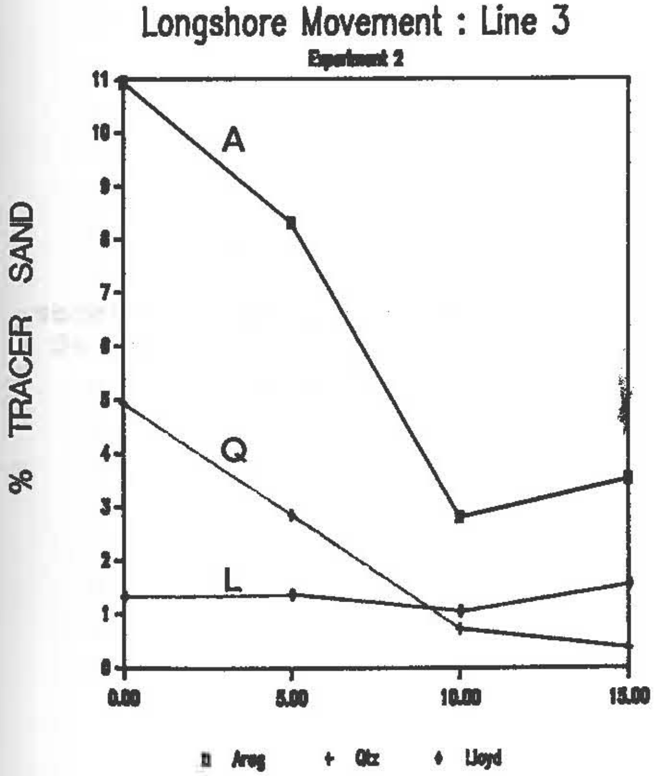

Longshore Movement : Line 1

Experiment 2

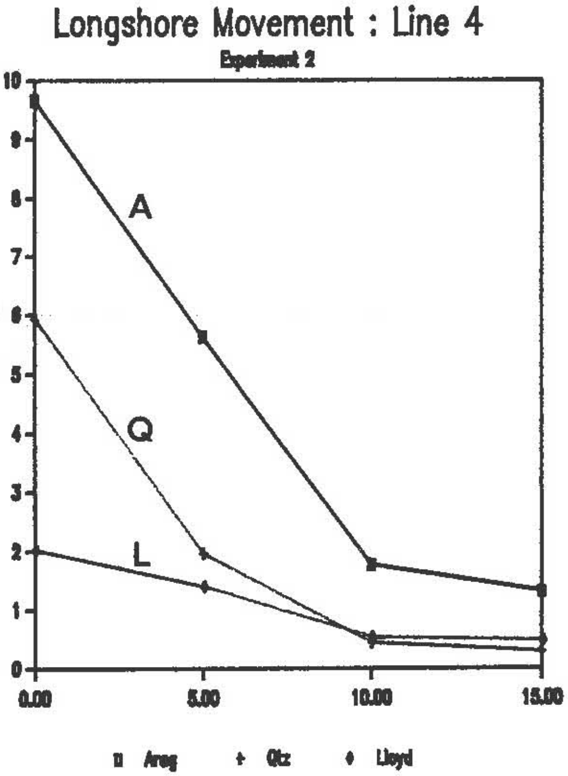

Longshore Movement : Line 2

Experiment 2

DISTANCE FROM INJECTION (M)


Longshore Movement : Line 3

Experiment 2


Longshore Movement : Line 4

Experiment 2

DISTANCE FROM INJECTION (M)

Figure 47

Onshore-offshore tracer
movement along line #I
in exper.2

Figure 48

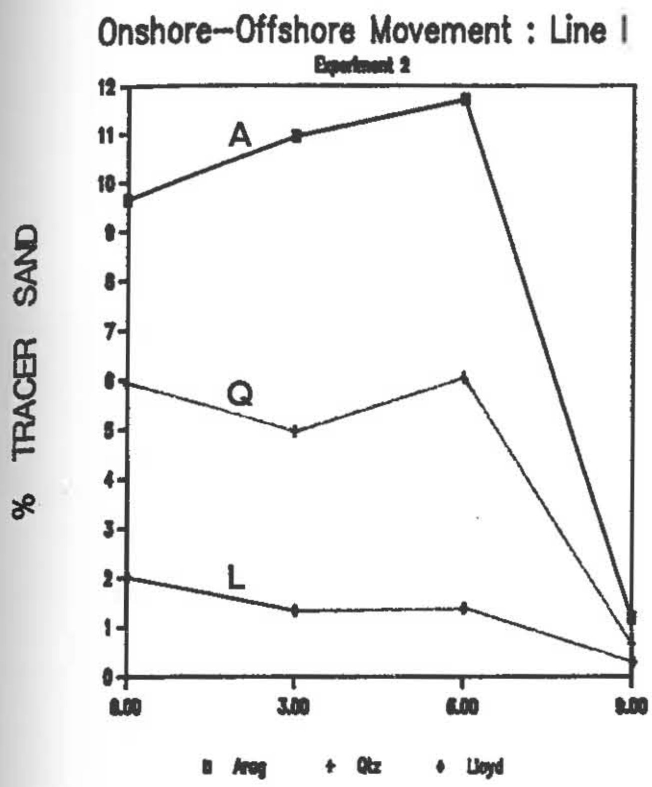
Onshore-offshore tracer
movement along line #A
in exper.2

Figure 49

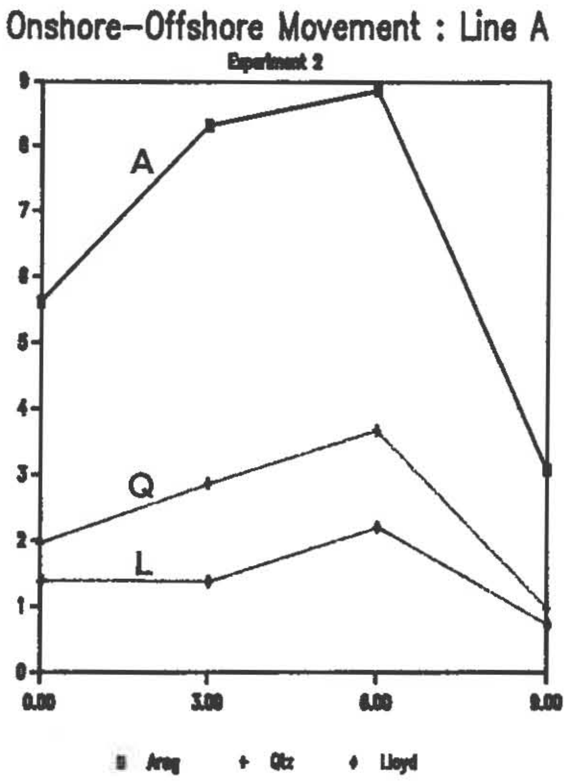
Onshore-offshore tracer
movement along line #B
in exper.2

Figure 50

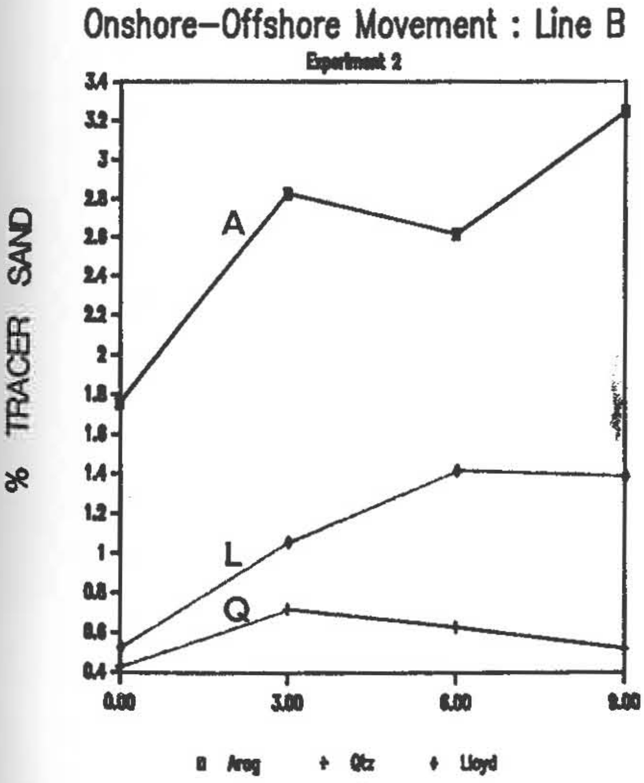
Onshore-offshore tracer
movement along line #C
in exper.2


Onshore–Offshore Movement : Line I

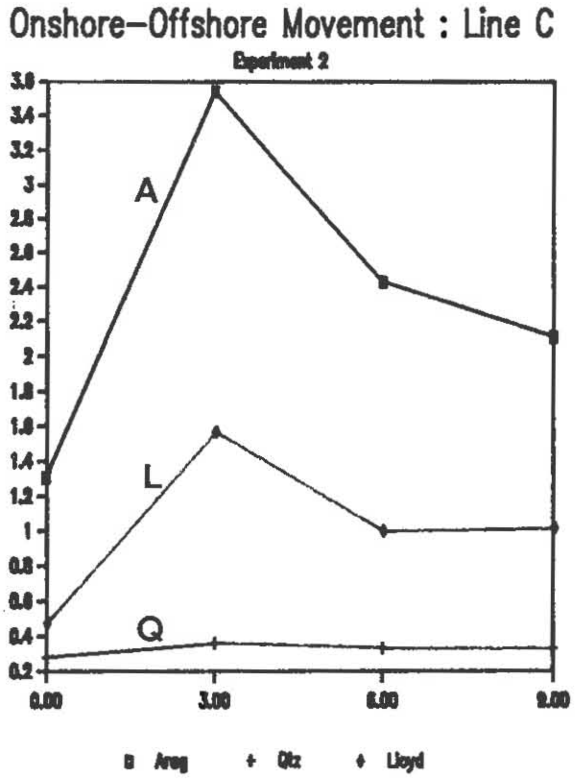
Experiment 2


Onshore–Offshore Movement : Line A

Experiment 2


Onshore–Offshore Movement : Line B

Experiment 2


Onshore–Offshore Movement : Line C

Experiment 2

1 and 2. Most importantly, they illustrate the relative amounts of tracer sand remaining on the injection line, i.e. the lag amounts that have not been transported. The first four Figures (31 to 34) summarize the net longshore and net onshore-offshore movements. There is a pattern of higher percentages of aragonite remaining at nearly every point in the transect with smaller percentages of quartz and even smaller fractions of the Lloyd Beach sand. This abundance of aragonite is especially prominent at the injection line implying the least amount of transport throughout the study. The same relative persistence of aragonite exists in both the longshore and onshore-offshore directions. Since this study was designed to examine the relative variations in transport between aragonite and quartz rather than their absolute differences, there should be a similarity in the results for both of the experiments that were conducted. Figures 31 to 34 verify that this indeed is the case despite the completely different nearshore conditions and the opposite directions of net transport that existed in experiments 1 and 2.

The mass of aragonite, quartz, and Lloyd Beach sand present at each station in the experimental grids was calculated based on the percent tracer present and the mean density of each size fraction. Table 11 summarizes the mass found at each individual sampling station. These data are plotted in Figures 51 and 52 as grams tracer per

TABLE 11
MASS IN GRAMS REMAINING AT INDIVIDUAL SAMPLING STATIONS UPON COMPLETION OF EXPERIMENTS 1 AND 2

Experiment 1

Station	Arag	Qtz	Lloyd
I-1	8.53	13.32	6.25
I-2	13.96	12.51	10.02
I-3	16.45	12.03	9.76
I-4	4.78	7.41	2.86
I-5	8.14	10.23	3.21
AN-1	2.06	1.14	1.60
AN-2	3.39	3.09	2.80
AN-3	15.66	9.40	13.31
AN-4	17.57	12.94	15.06
AN-5	10.61	11.10	6.44
BN-1	0.01	0.03	0.09
BN-2	0.14	0.16	0.37
BN-3	1.46	1.42	1.36
BN-4	3.41	4.86	4.31
BN-5	0.81	0.50	0.71
AS-1	4.27	5.92	4.51
AS-2	1.80	2.68	1.52
AS-3	0.31	0.48	0.35
AS-4	0.20	0.05	0.26
AS-5	0.03	0.03	0.09

Experiment 2

I-1	0.70	1.02	0.20
I-2	8.22	9.90	2.03
I-3	16.16	14.02	2.98
I-4	22.11	20.20	5.85
A-1	2.74	1.70	1.71
A-2	6.39	5.20	2.58
A-3	8.40	9.10	2.17
A-4	13.20	9.48	4.47
B-1	1.09	0.84	1.57
B-2	3.74	0.76	2.26
B-3	4.02	0.77	1.61
B-4	3.80	1.40	0.66
C-1	0.23	0.41	0.19
C-2	1.59	0.32	0.54
C-3	3.51	0.19	1.71
C-4	3.61	1.05	0.90

Figure 51

Contour plot comparing tracer mass movement of aragonite, quartz, and Lloyd Beach in experiment 1

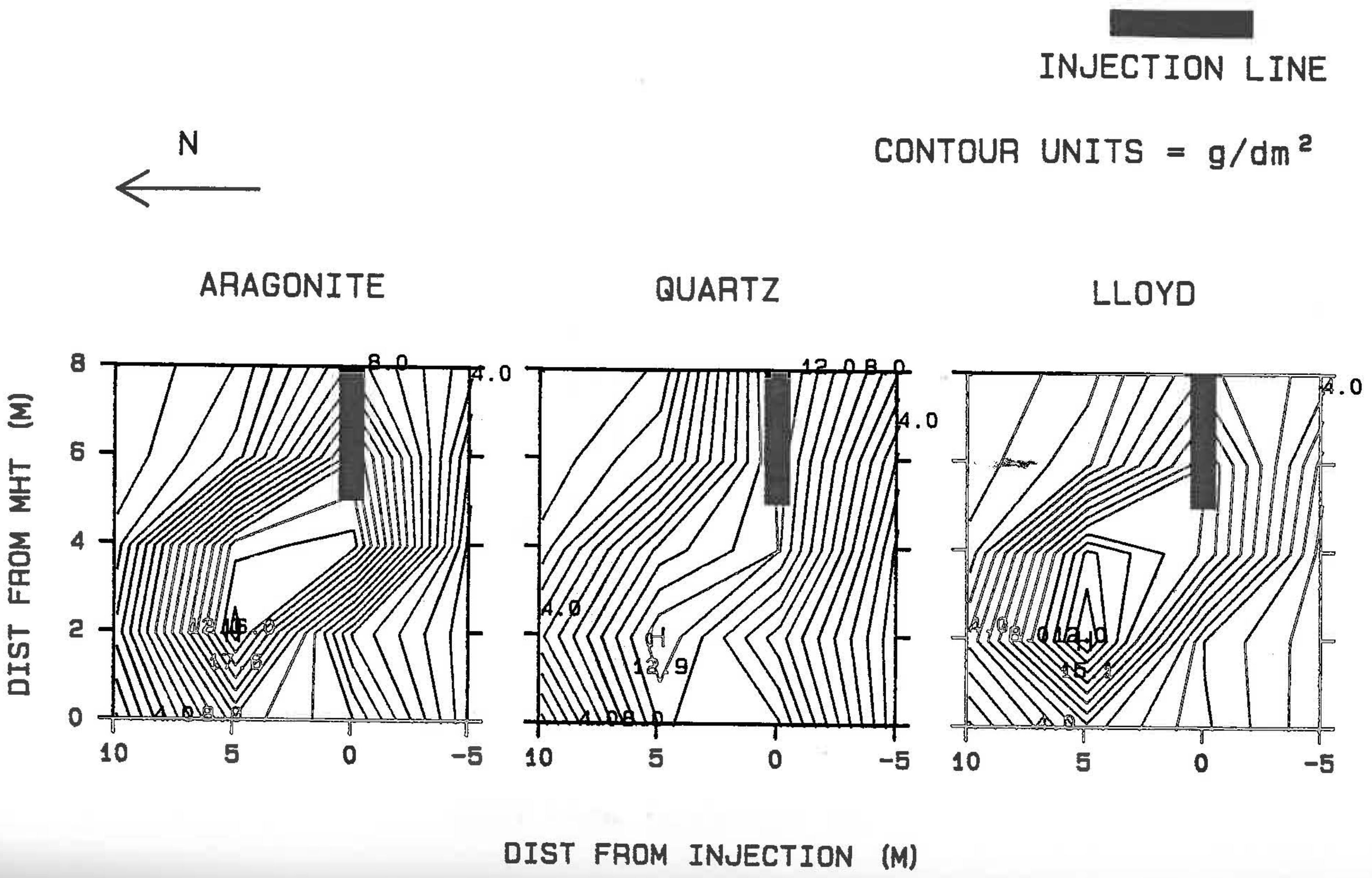
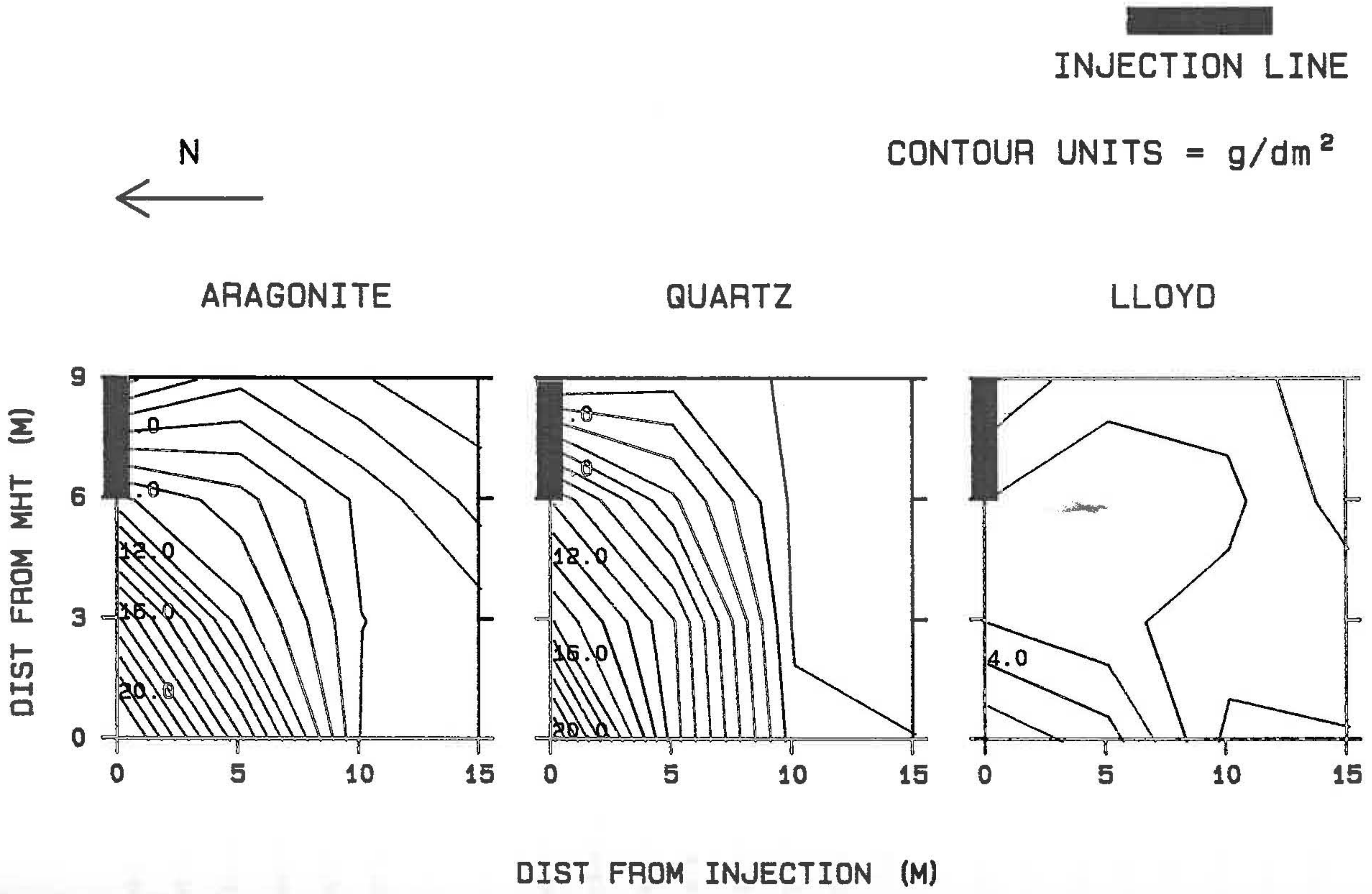

INJECTION LINE
CONTOUR UNITS = g/dm²
N
ARAGONITE
QUARTZ
LLOYD
DIST FROM MHT (M)
0
2
4
6
8
10
5
0
-5
DIST FROM INJECTION (M)
8.0
4.0
12.0
16.0
17.5
4.0
8.0
12.0
8.0
4.0
12.9
15.1

Figure 52

Contour plot comparing tracer mass movement of aragonite, quartz, and Lloyd Beach in experiment 2


INJECTION LINE
CONTOUR UNITS = g/dm²
N
ARAGONITE
QUARTZ
LLOYD
DIST FROM MHT (M)
0
3
6
9
.0
.0
12.0
16.0
20.0
.0
.0
12.0
16.0
20.0
4.0
0
5
10
15
DIST FROM INJECTION (M)

square decimeter. These contour plots indicate the direction and magnitude of tracer movement from the injection line upon completion of experiments 1 and 2 for each of the individual 45 kilogram samples of aragonite, quartz, and Lloyd Beach sand. Details of the microscopic grain counts can be found in Appendix B.

Littoral Transport of Equal Size Fractions

The second phase in the analysis of the raw transport data addressed the question of what physical characteristics other than grain size influenced sand movement in the surf zone. Since each tracer sample was sieved into 12 sub-fractions before quantification, it was possible to compare equivalent grain sizes throughout the grid. The contribution of other sedimentary characteristics, such as density and grain shape, could then be assessed in the sediment transport process.

Tracer movement was evaluated along lines parallel and perpendicular to the beach within the experimental grid. Since 70-80 percent of the total mass in the aragonite, quartz, and Lloyd Beach samples is smaller than 1.0 phi (0.50mm), this analysis was confined to the 1.0-3.5 phi (0.50-0.09mm) grain size classes. Also, with a very small number of grains larger than 1.0 phi at the onset of the study, the recovery rate for these larger size classes was too small to yield representative results.

At the onset of the tracer studies, the initial size

Figure 53

Longshore tracer movement of 1.0 phi size fraction in exper.1

Figure 54

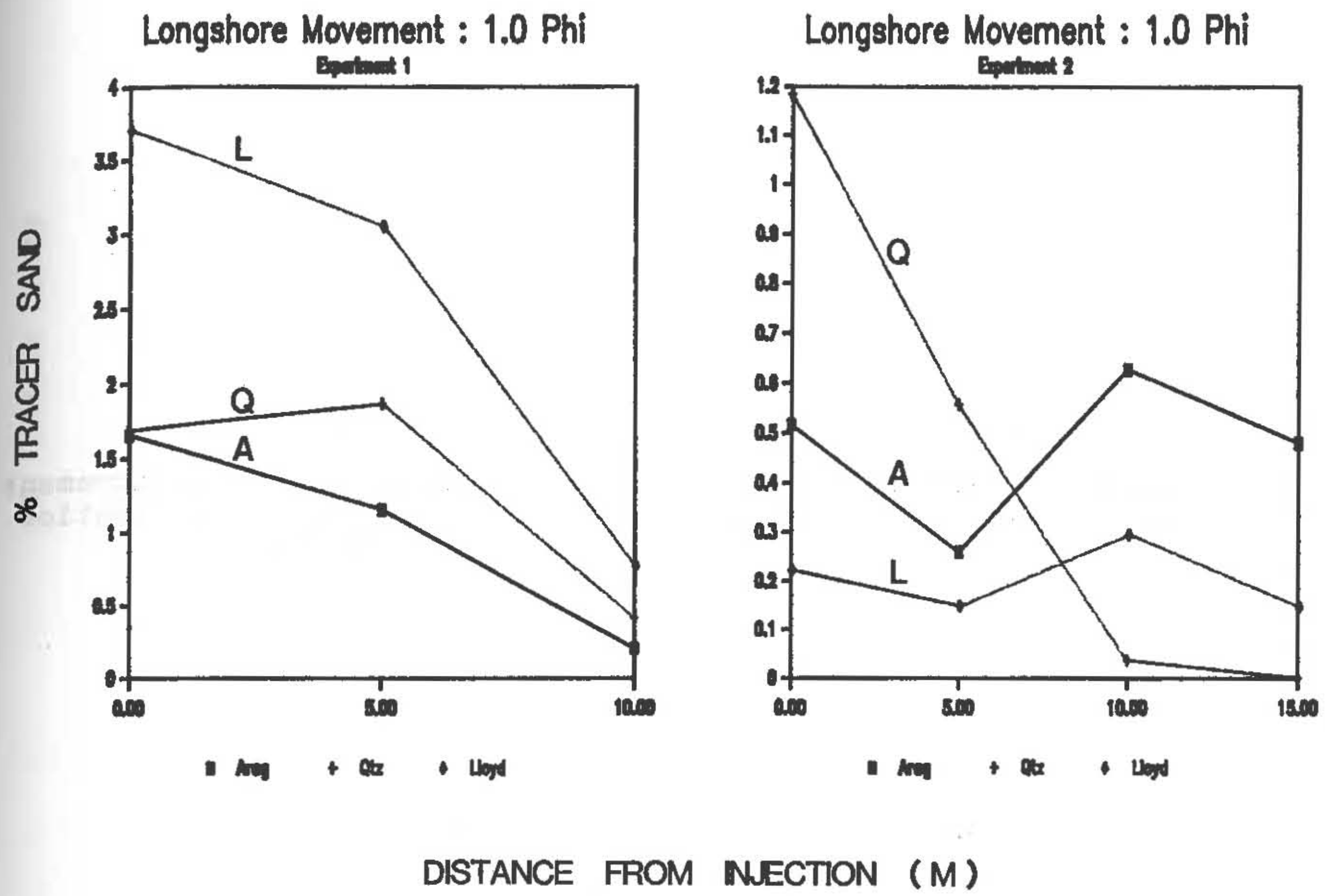
Longshore tracer movement of 1.0 phi size fraction in exper.2

Figure 55

Onshore-offshore tracer movement of 1.0 phi size fraction in exper.1

Figure 56

Onshore-offshore tracer movement of 1.0 phi size fraction in exper.2


Longshore Movement : 1.0 Phi
Experiment 1
Longshore Movement : 1.0 Phi
Experiment 2
% TRACER SAND
L
Q
A
4
3.5
3
2.5
2
1.5
1
0.5
0
0.00
5.00
10.00
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.00
5.00
10.00
15.00
Arag
Qtz
Lloyd
DISTANCE FROM INJECTION (M)

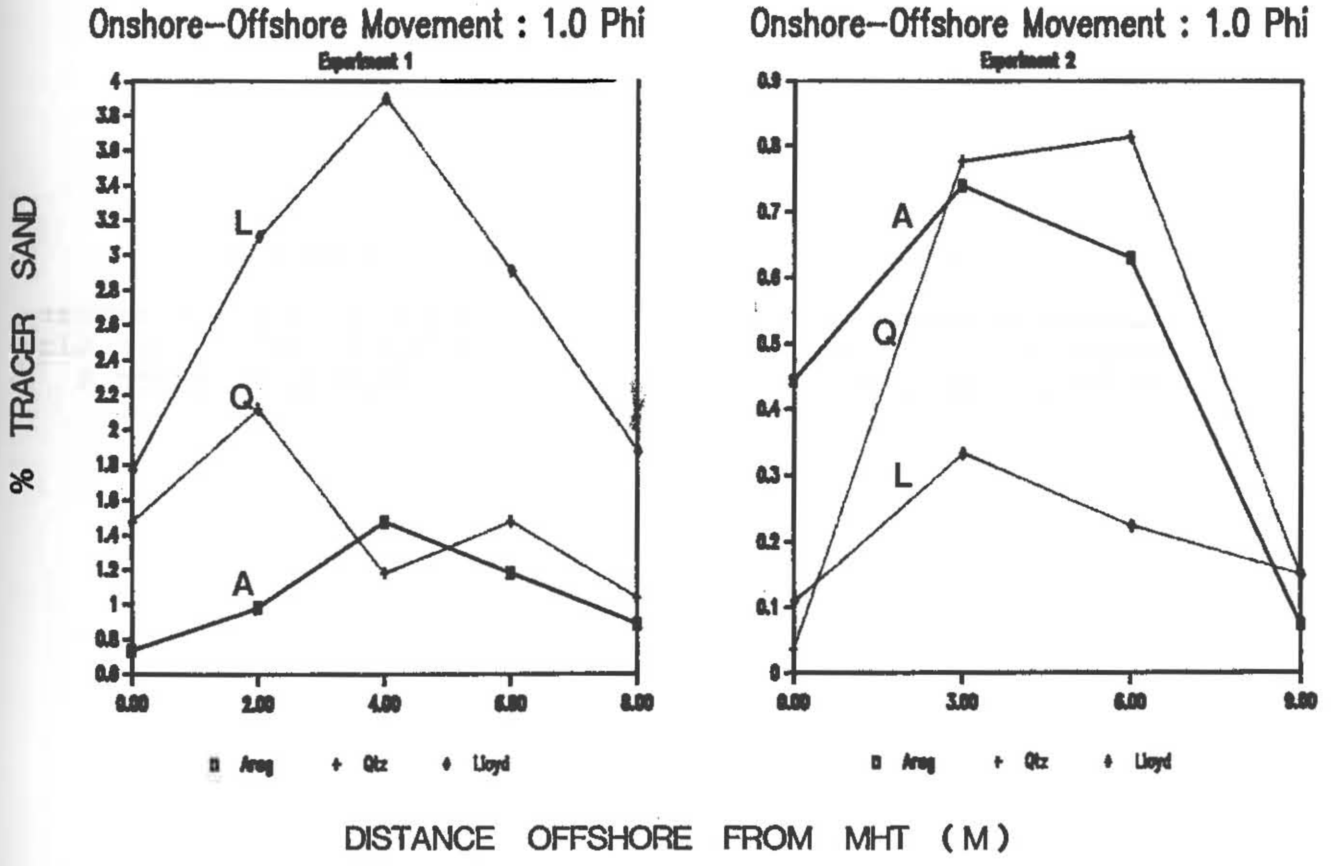

Onshore--Offshore Movement : 1.0 Phi
Experiment 1
Onshore--Offshore Movement : 1.0 Phi
Experiment 2
% TRACER SAND
L
Q
A
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.00
2.00
4.00
6.00
8.00
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.00
3.00
6.00
9.00
Arag
Qtz
Lloyd
DISTANCE OFFSHORE FROM MHT (M)

Figure 57

Longshore tracer movement of 1.5 phi size fraction in exper.1

Figure 58

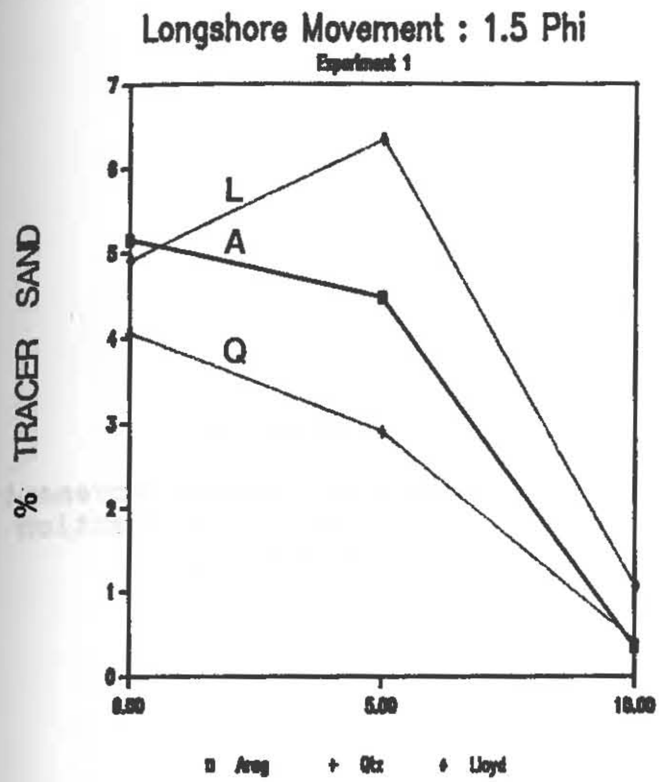
Longshore tracer movement of 1.5 phi size fraction in exper.2

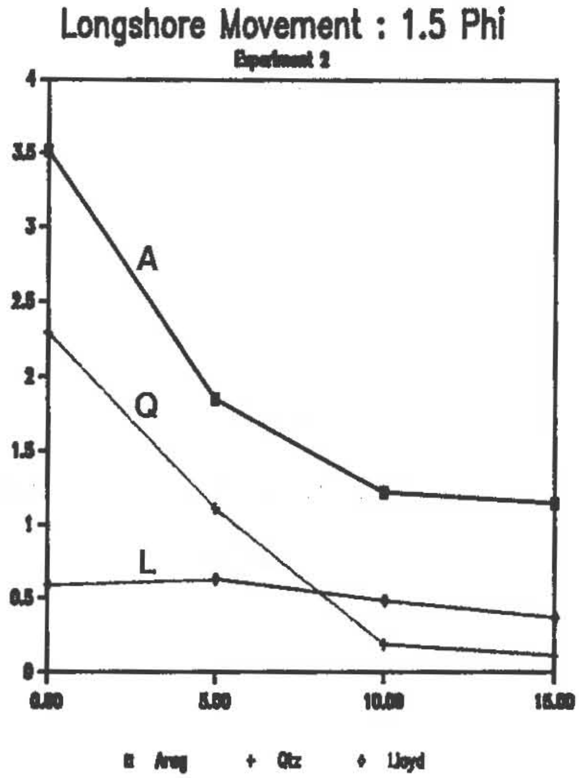
Figure 59

Onshore-offshore tracer movement of 1.5 phi size fraction in exper.1

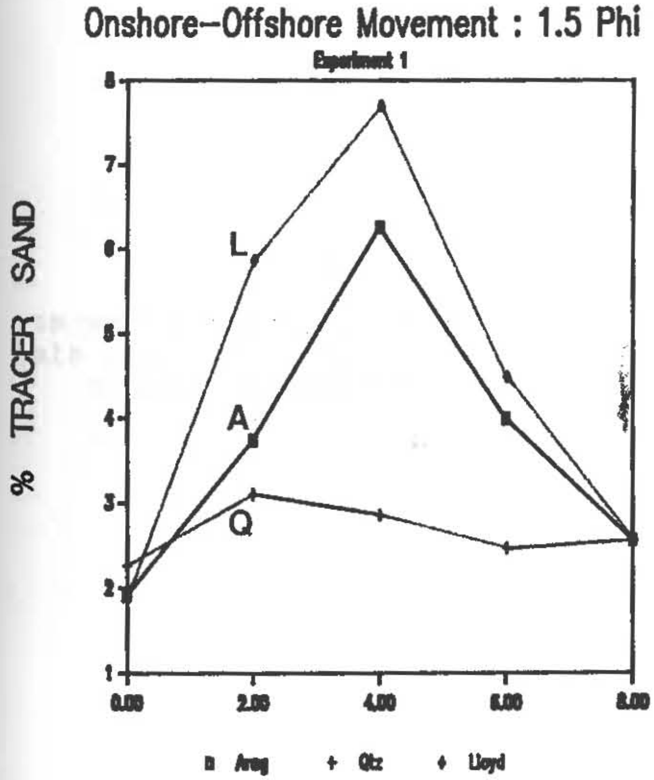
Figure 60

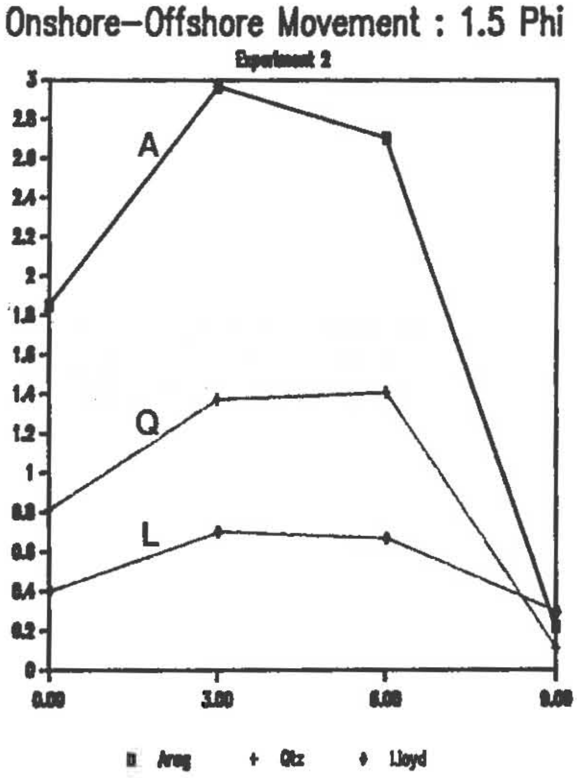
Onshore-offshore tracer movement of 1.5 phi size fraction in exper.2





DISTANCE FROM INJECTION (M)





DISTANCE OFFSHORE FROM MHT (M)

Figure 61

Longshore tracer movement of 2.0 phi size fraction in exper.1

Figure 62

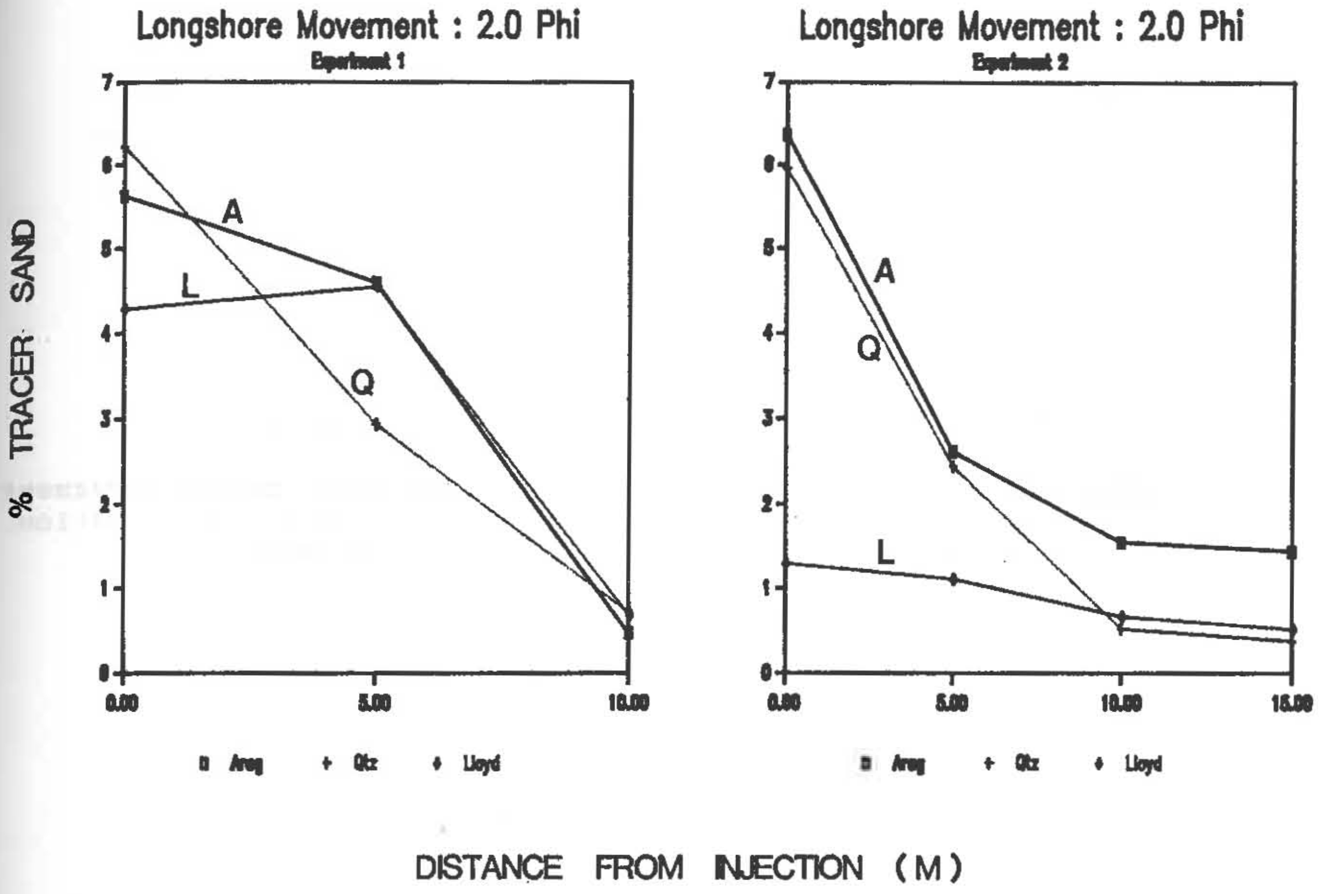
Longshore tracer movement of 2.0 phi size fraction in exper.2

Figure 63

Onshore-offshore tracer movement of 2.0 phi size fraction in exper.1

Figure 64

Onshore-offshore tracer movement of 2.0 phi size fraction in exper.2


Longshore Movement : 2.0 Phi
Experiment 1
Longshore Movement : 2.0 Phi
Experiment 2
% TRACER SAND
0
1
2
3
4
5
6
7
0.00
5.00
10.00
15.00
A
L
Q
Areg
Qtz
Lloyd
DISTANCE FROM INJECTION (M)

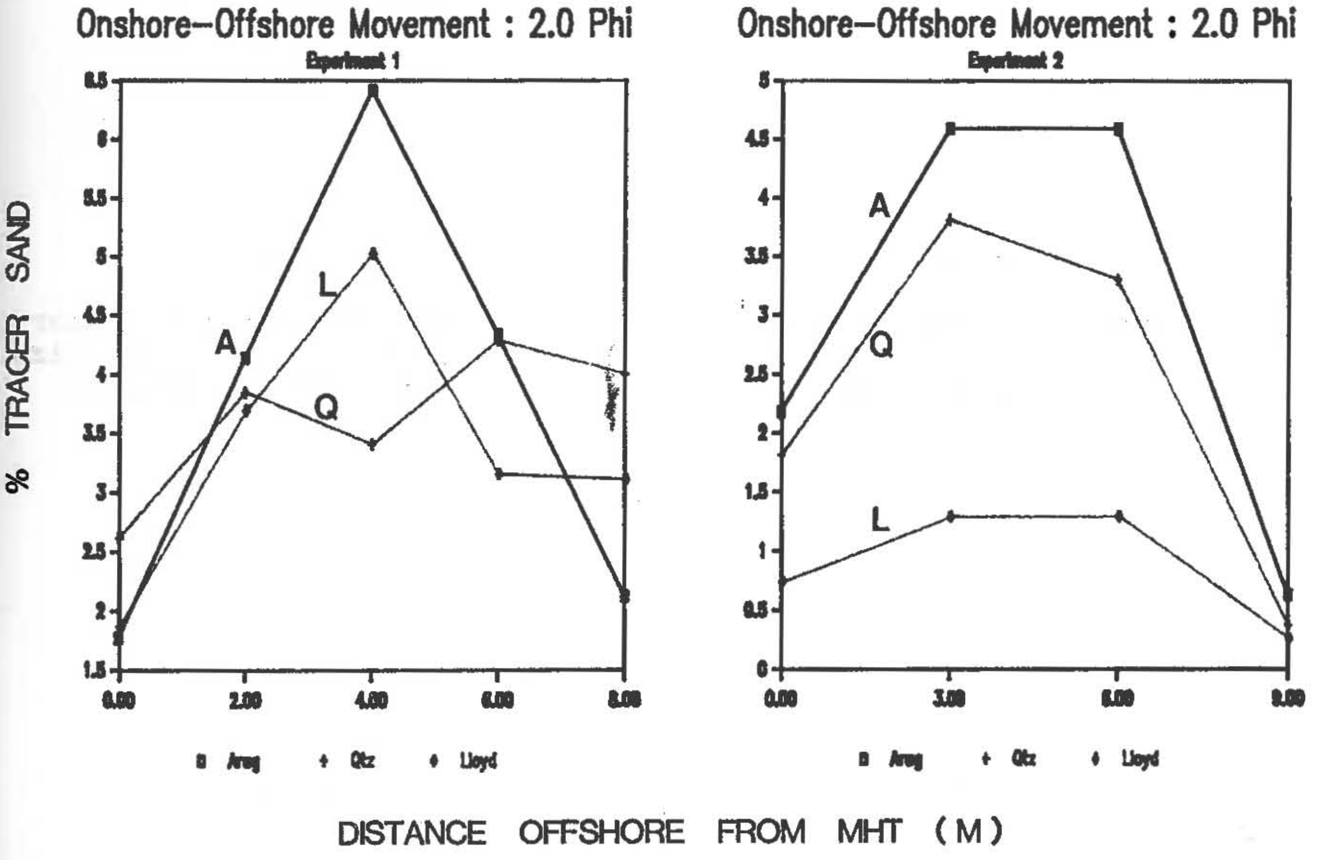

Onshore–Offshore Movement : 2.0 Phi
Experiment 1
Onshore–Offshore Movement : 2.0 Phi
Experiment 2
% TRACER SAND
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0.00
2.00
4.00
6.00
8.00
3.00
6.00
9.00
A
L
Q
Areg
Qtz
Lloyd
DISTANCE OFFSHORE FROM MHT (M)

Figure 65

Longshore tracer movement of 2.5 phi size fraction in exper.1

Figure 66

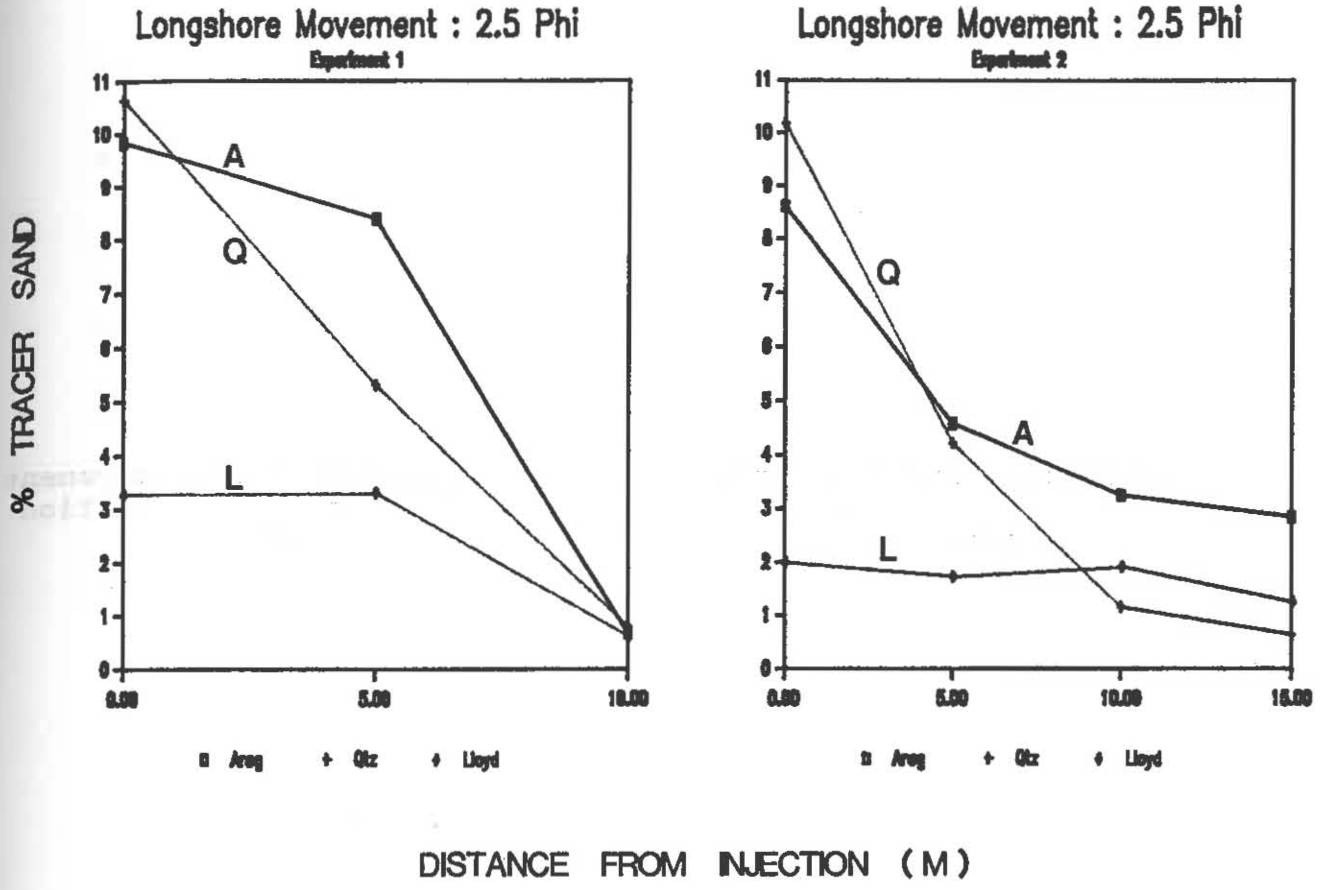
Longshore tracer movement of 2.5 phi size fraction in exper.2

Figure 67

Onshore-offshore tracer movement of 2.5 phi size fraction in exper.1

Figure 68

Onshore-offshore tracer movement of 2.5 phi size fraction in exper.2


Longshore Movement : 2.5 Phi
Experiment 1
Longshore Movement : 2.5 Phi
Experiment 2
% TRACER SAND
0
1
2
3
4
5
6
7
8
9
10
11
A
Q
L
0.00
5.00
10.00
15.00
Arag
Qtz
Lloyd
DISTANCE FROM INJECTION (M)

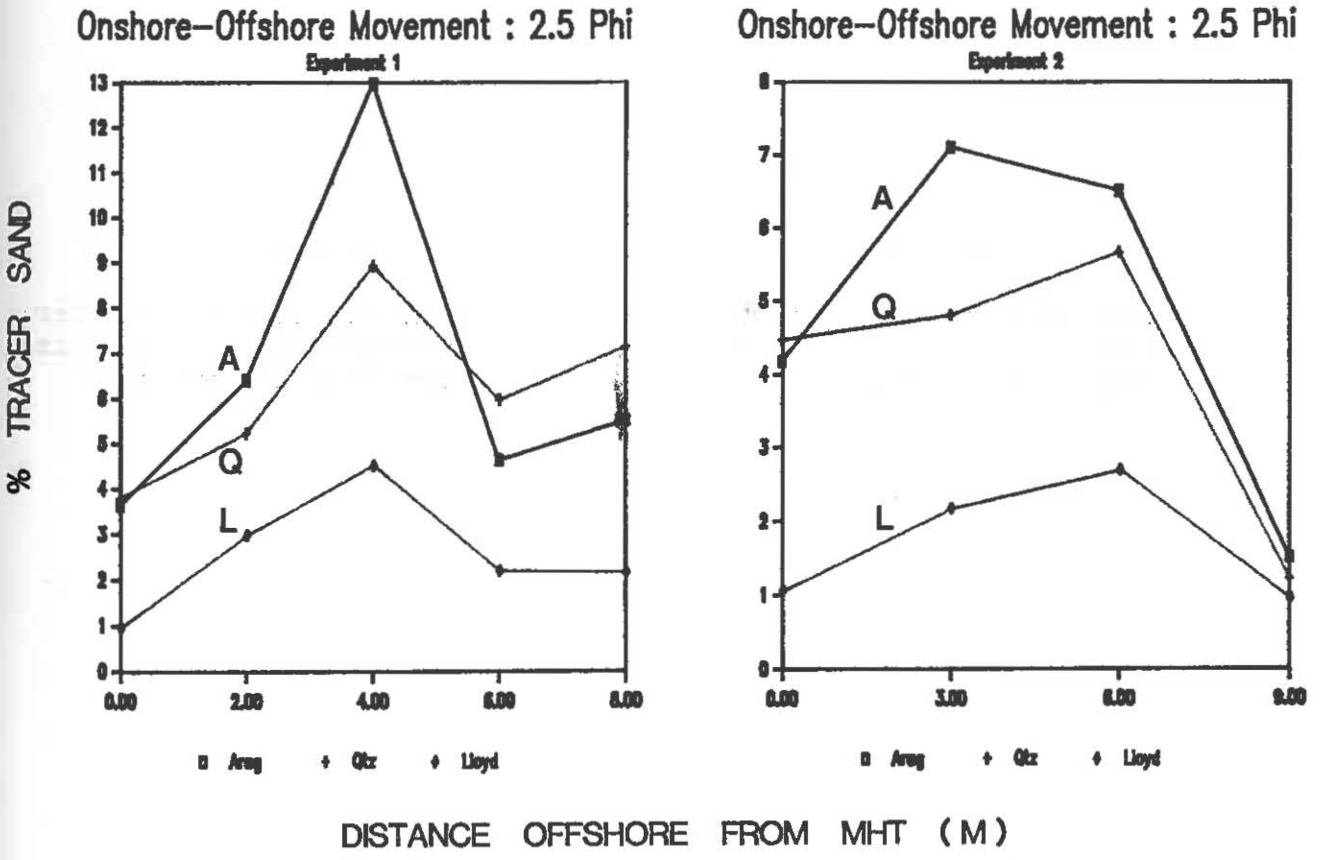

Onshore–Offshore Movement : 2.5 Phi
Experiment 1
Onshore–Offshore Movement : 2.5 Phi
Experiment 2
% TRACER SAND
0
1
2
3
4
5
6
7
8
9
10
11
12
13
A
Q
L
0.00
2.00
4.00
6.00
8.00
3.00
9.00
Arag
Qtz
Lloyd
DISTANCE OFFSHORE FROM MHT (M)

Figure 69

Longshore tracer movement of 3.0 phi size fraction in exper.1

Figure 70

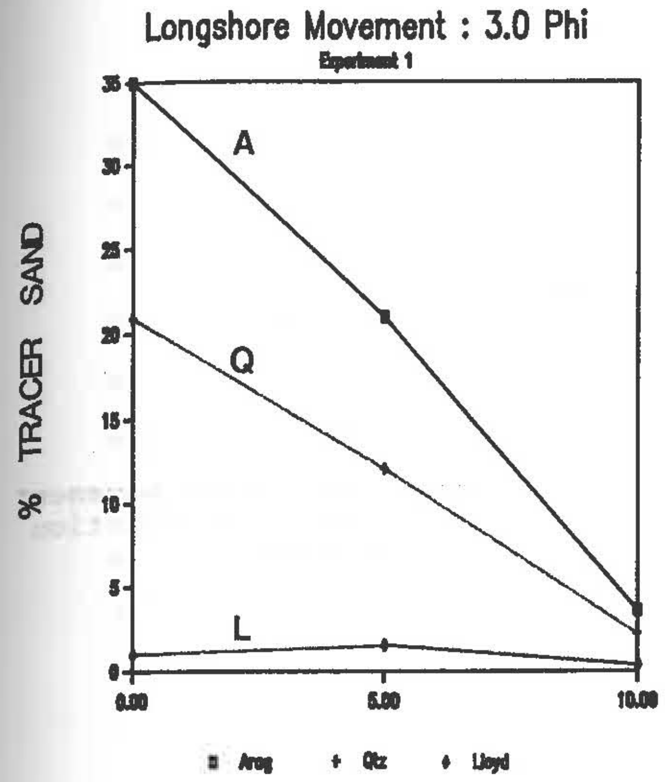
Longshore tracer movement of 3.0 phi size fraction in exper.2

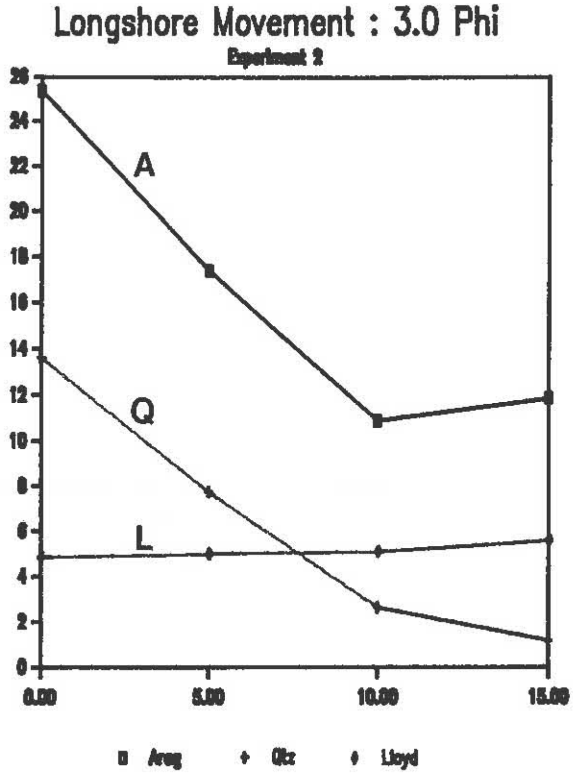
Figure 71

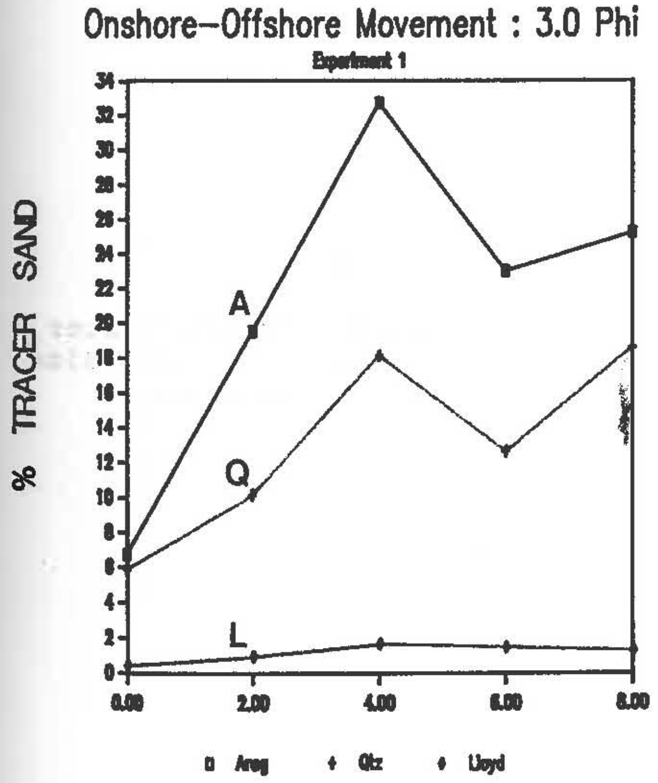
Onshore-offshore tracer movement of 3.0 phi size fraction in exper.1

Figure 72

Onshore-offshore tracer movement of 3.0 phi size fraction in exper.2


Longshore Movement : 3.0 Phi
Experiment 1
% TRACER SAND
A
Q
L
0
5
10
15
20
25
30
35
0.00
5.00
10.00
Arag
Qtz
Lloyd


Longshore Movement : 3.0 Phi
Experiment 2
A
Q
L
0
2
4
6
8
10
12
14
16
18
20
22
24
26
0.00
5.00
10.00
15.00
Arag
Qtz
Lloyd
DISTANCE FROM INJECTION (M)


Onshore-Offshore Movement : 3.0 Phi
Experiment 1
% TRACER SAND
A
Q
L
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
0.00
2.00
4.00
6.00
8.00
Arag
Qtz
Lloyd

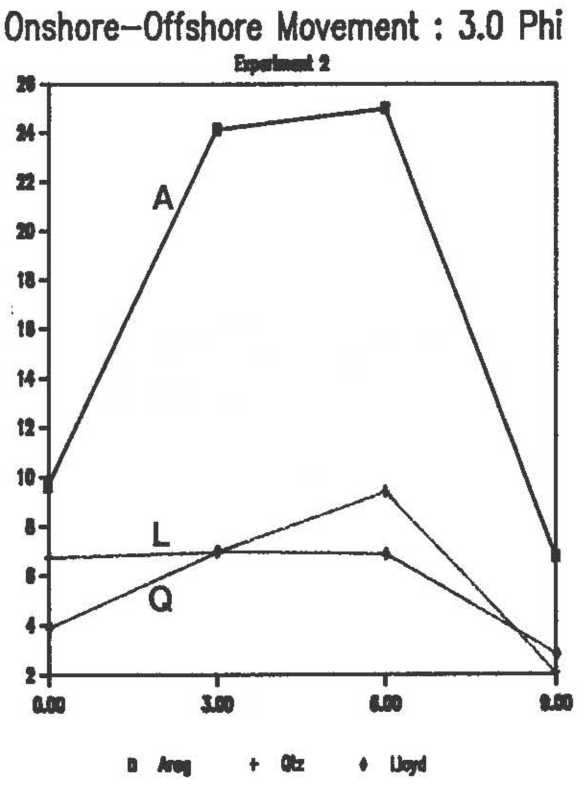

Onshore-Offshore Movement : 3.0 Phi
Experiment 2
A
L
Q
2
4
6
8
10
12
14
16
18
20
22
24
26
0.00
3.00
6.00
9.00
Arag
Qtz
Lloyd
DISTANCE OFFSHORE FROM MHT (M)

Figure 73

Longshore tracer movement of 3.5 phi size fraction in exper.1

Figure 74

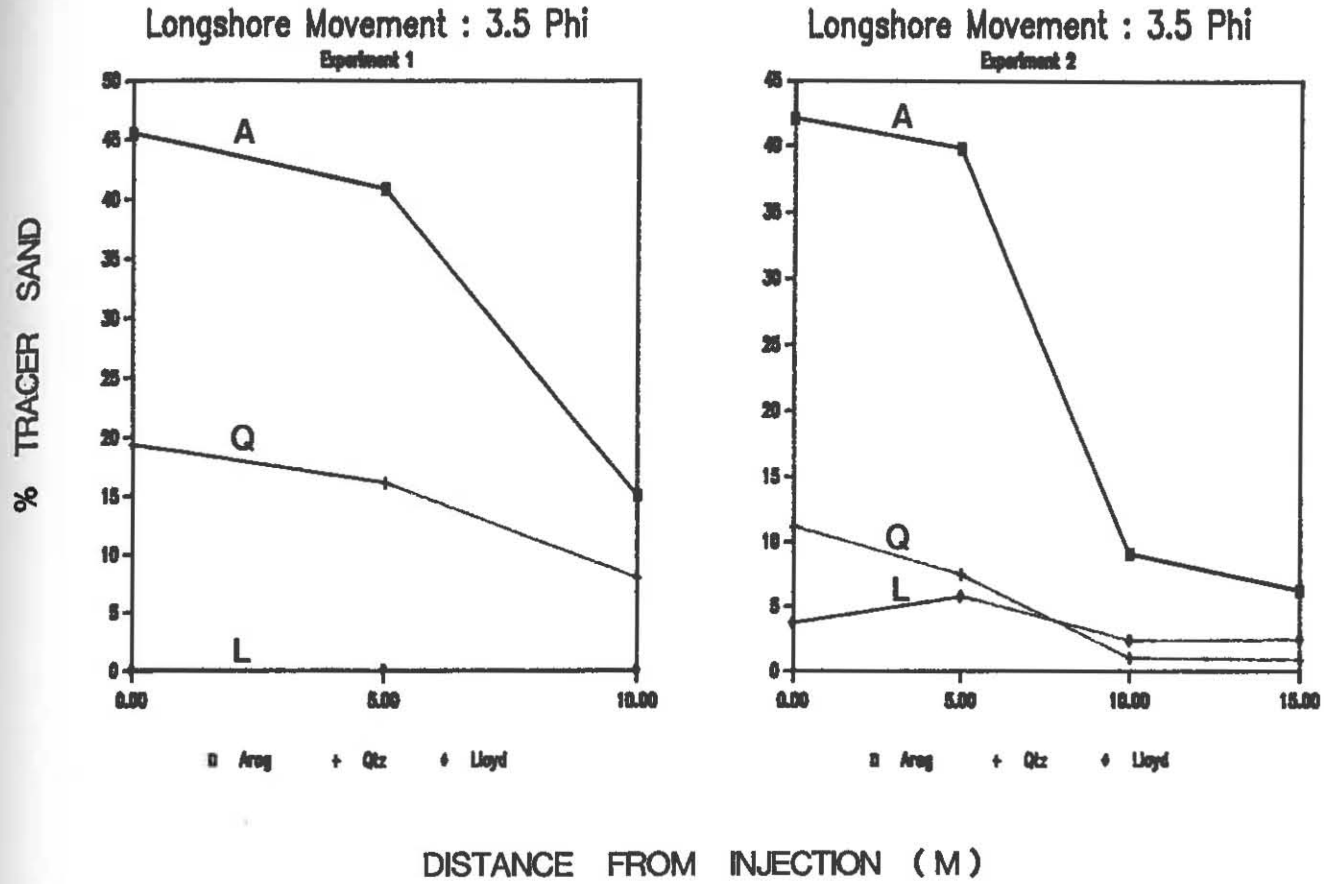
Longshore tracer movement of 3.5 phi size fraction in exper.2

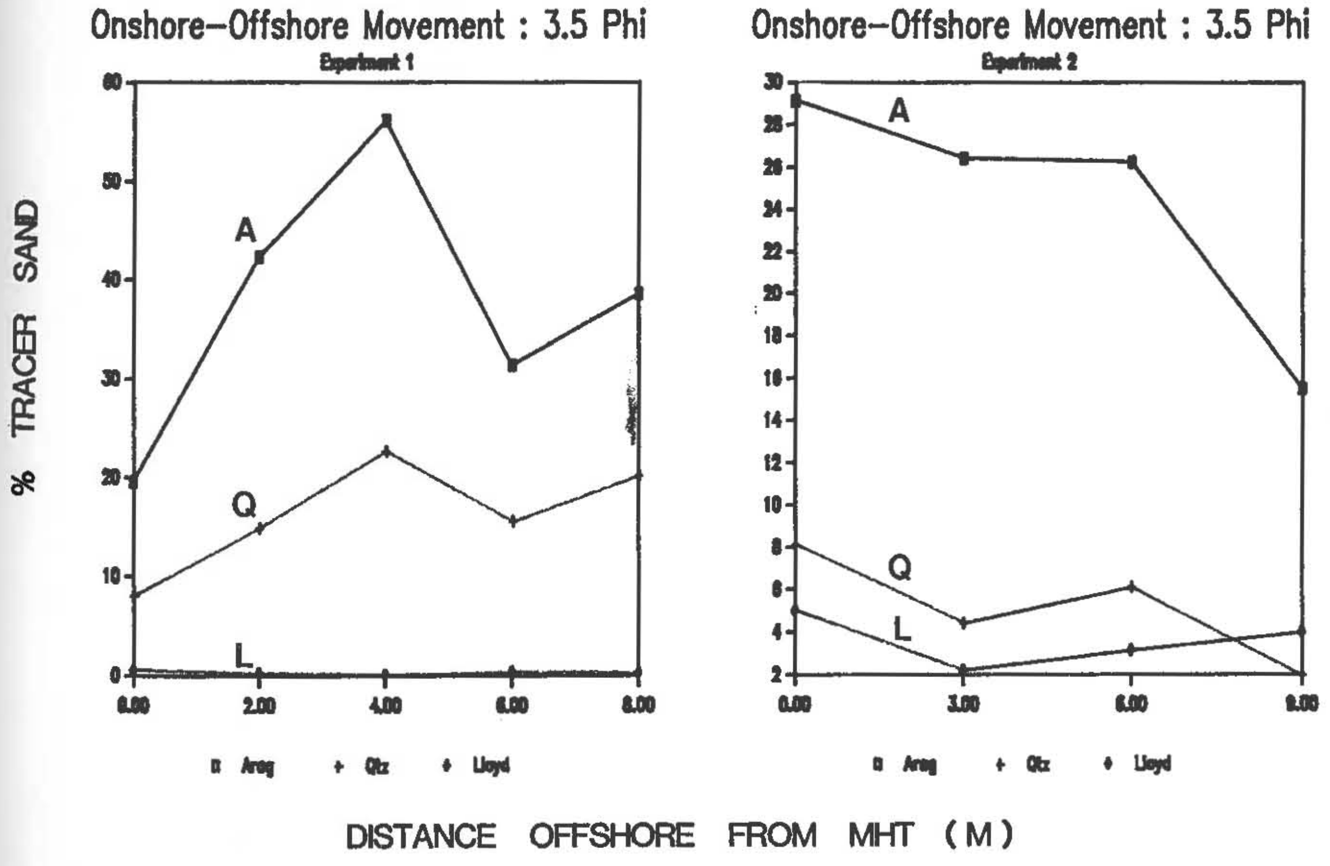
Figure 75

Onshore-offshore tracer movement of 3.5 phi size fraction in exper.1

Figure 76

Onshore-offshore tracer movement of 3.5 phi size fraction in exper.2


Longshore Movement : 3.5 Phi
Experiment 1
% TRACER SAND
0
5
10
15
20
25
30
35
40
45
50
A
Q
L
0.00
5.00
10.00
Arag
Qtz
Lloyd
Longshore Movement : 3.5 Phi
Experiment 2
0
5
10
15
20
25
30
35
40
45
A
Q
L
0.00
5.00
10.00
15.00
Arag
Qtz
Lloyd
DISTANCE FROM INJECTION (M)


Onshore-Offshore Movement : 3.5 Phi
Experiment 1
% TRACER SAND
0
10
20
30
40
50
60
A
Q
L
0.00
2.00
4.00
6.00
8.00
Arag
Qtz
Lloyd
Onshore-Offshore Movement : 3.5 Phi
Experiment 2
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
A
Q
L
0.00
3.00
6.00
9.00
Arag
Qtz
Lloyd
DISTANCE OFFSHORE FROM MHT (M)

frequency distributions for the aragonite, quartz, and Lloyd Beach samples were different. Figures 53 to 76 graphically show the percent aragonite, quartz, and Lloyd Beach sand remaining along various lines in the grid for the equal size data upon completion of experiments 1 and 2. These figures indicate that aragonite experienced less transport in the size fractions smaller than 0.25mm as evidenced by its increased abundance at the injection line (distance 0). In the grain sizes larger than 0.25mm, the tracer data is less conclusive. The results from experiment 2 still exhibit increased amounts of aragonite (i.e. less aragonite transported) up until 1.0 phi (0.50mm) although this trend was not apparent in experiment 1.

In order to remove the effects of the initial differences in the size distributions a second analysis was performed which examined the initial and final ratios of aragonite to quartz at the injection line for the grain size classes between 1.0 phi and 3.5 phi. Table 12 shows the aragonite to quartz ratios (A/Q) in each size class calculated from the lab prior to the introduction of these materials on the beach. Theoretically, if the two samples were to undergo the same magnitude of transport for the duration of the study, the final A/Q ratios after extraction throughout the grid would be identical to the initial values. The initial and final A/Q ratios at the injection line are presented in Table 13 and plotted in

TABLE 12

FREQUENCY PERCENT AND RATIO OF ARAGONITE TO QUARTZ PRIOR TO BEACH EMPLACEMENT

Phi Size(mm)	Freq. % Arag	Freq. % Qtz	Ratio A/Q
1.00 (0.50)	3.58	2.26	1.58
1.50 (0.35)	19.21	11.54	1.66
2.00 (0.25)	19.36	21.58	0.90
2.50 (0.18)	22.64	35.08	0.65
3.00 (0.125)	16.34	14.32	1.14
3.50 (0.09)	9.49	7.93	1.20

TABLE 13

RATIO OF ARAGONITE TO QUARTZ REMAINING AT INJECTION LINE BY SIZE FRACTION BEFORE AND AFTER EXPERIMENTS 1 AND 2

Experiment 1

Phi Size(mm)	Initial A/Q	Final A/Q
1.00 (0.50)	1.58	0.98
1.50 (0.35)	1.66	1.27
2.00 (0.25)	0.90	0.90
2.50 (0.18)	0.65	0.92
3.00 (0.125)	1.14	1.67
3.50 (0.09)	1.20	2.34

Experiment 2

1.00 (0.50)	1.58	0.44
1.50 (0.35)	1.66	1.53
2.00 (0.25)	0.90	1.07
2.50 (0.18)	0.65	0.85
3.00 (0.125)	1.14	1.86
3.50 (0.09)	1.20	3.74

Figure 77

Plot of the initial and final aragonite to quartz (A/Q) ratios for grain sizes 0.50mm to 0.09mm

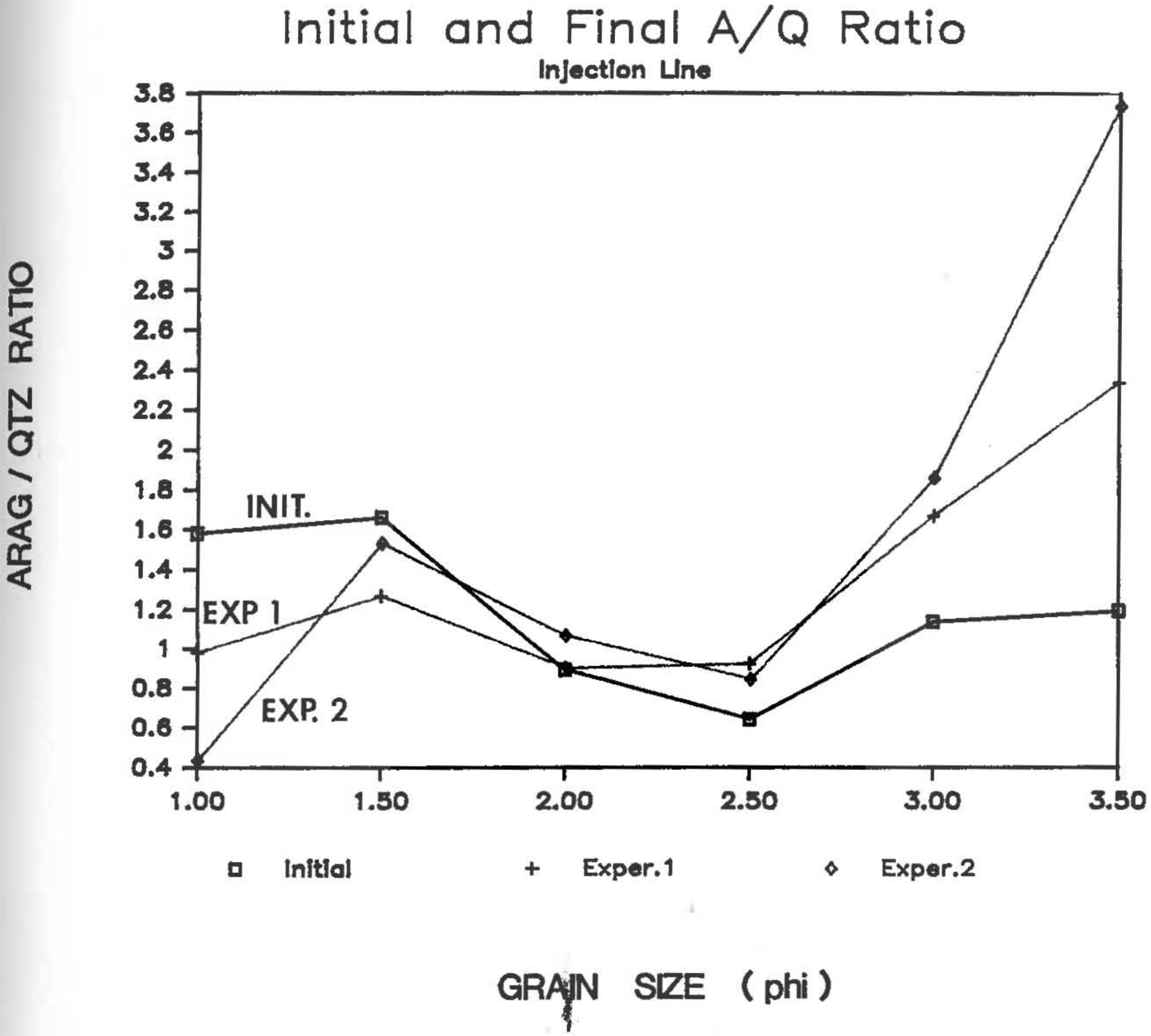

Initial and Final A/Q Ratio
Injection Line
ARAG / QTZ RATIO
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
INIT.
EXP 1
EXP. 2
1.00
1.50
2.00
2.50
3.00
3.50
□ Initial
+ Exper.1
◇ Exper.2
GRAIN SIZE (phi)

Figure 77. The results show that in the larger sizes from 2.0-1.0 phi (0.25-0.50mm), the final A/Q ratio is less than the initial, indicating a net loss of aragonite relative to the quartz. In the smaller grain sizes from 2.0-3.5 phi (0.25-0.09mm), the final A/Q ratio at the injection line is greater than the initial ratio which indicates that there has been a greater net loss of quartz relative to the aragonite. Thus, on a relative granular basis, the aragonite experienced the least amount of transport in the smallest grain sizes; whereas, the quartz underwent the least amount of transport in the larger grain sizes. Again, the data in both experiments 1 and 2 support this outcome despite the large variation in the wave and wind conditions that existed in the two studies.

V. DISCUSSION

Sediment Transport Characteristics

The sediment transport system in the surf zone is a complex interrelationship between a large number of variables. The physical characteristics of the sediments must be considered as well as parameters pertaining to the background beach morphology as well as the various modes of transport. It is well known (Steidtman, 1982; Blackley and Heathershaw, 1982) that selective transport according to size, shape, and density plays an important role in the sorting of beach sediments by waves and tidal currents; however, the exact mechanisms involved are poorly understood. There is also uncertainty as to the relative amount of sediment movement occurring within the bed load (via traction and saltation) and suspension load fractions on the beach. Komar (1978) has estimated that the suspended load transport may only constitute a maximum of 25% but more probably as little as 10% or less of the total transport on beaches. Nielson (1983) showed that for grain sizes larger than 0.5 mm the likelihood of entrainment into suspension decreases with increasing grain size, whereas, for the finer material (diameter less than 0.5 mm) the amount of suspended material is proportional to the amount available in the bed material. For the present study all three test materials possess a mean grain size that is less than 0.5 mm, therefore movement in suspension would be the predominant mode of transport according to Nielson's hypothesis. It seems likely that a great deal of movement must be taking place in intermittent suspension, a type of motion that is typical of fine-to-medium grained sand in most subaqueous environments. These differing modes of grain motion not only result in different rates of sediment transport for different size, density, and shape fractions, but will vary from beach to beach based on the specific wave conditions, slope, and background grain texture that are present.

It would be extremely simplistic to expect that one specific mechanism would explain the transport variability between aragonite and quartz. Intuitively, it seems apparent that the processes controlling the entrainment and transport of these materials are not dissimilar from those involved in the origin of heavy mineral beach placer deposits, where selective sorting by size, density, and shape occurs by means of constant reworking in the surf zone. A thorough discussion of the concentrations and settling velocity relationships of light and heavy minerals in placer and sedimentary deposits in general can be found in McIntyre (1959), Hand (1967), Briggs (1965), White and Williams (1967), Grigg and Rathbun (1969), Lowright et al.(1972), Stapor (1973), Slingerland (1977;1980), and Sallenger (1979).

In sedimentary deposits and on active beaches, it is common to observe grains of different sizes, shapes, and densities coexisting together, i.e. in dynamic equilibrium. Hydraulic equivalence is the most common interpretation. This concept, demonstrated theoretically by Rubey (1933), was stated by McIntyre (1959) as follows: If two detrital grains are associated in a deposit, they have responded similarly to the same hydraulic conditions. Thus if two grains of different densities are found in the same deposit, they are hydraulically equivalent, and the difference in size between them is a result of the hydraulic equivalence. Rubey (1933) considered density the most important factor in determining the hydraulic equivalence between any two minerals.

Using Stoke's Law of settling velocity $V = C(d-w)r^2$ where

V = particle fall velocity in cm/sec
d = particle density in g/cm3
w = fluid density in g/cm3
C = constant for a given temperature
r = radius of the particle in cm ,

it is possible to test whether two grains of differing sizes and densities are hydraulically equivalent by equating V1 and V2 according to their respective grain densities and particle diameters. By assuming w = 1, the result is that:

$$\frac{r1^2}{r2^2} = \frac{d2 - 1}{d1 - 1}$$

Not only can the two grains be compared to test for hydraulic equivalence but it is possible to estimate the extent of deviation from equivalence in order to assess the influence of other variables such as original source distance and compositional makeup. Based on this relationship (McIntyre, 1959), it is also possible to predict the theoretical size for a specific mineral type that can coexist in a given deposit by knowing that mineral's respective density. Since Stoke's Law of settling velocity and Rubey's hydraulic equivalence theorem both utilize density and not specific gravity, density estimations were reported rather than specific gravity (Table 7).

The significance of this concept for the present study is that for a given grain size, the predicted settling or fall velocity for the aragonite sample is greater than that for the quartz sample. This same result is obtained whether comparing equal grain sizes for both materials or for comparing their calculated mean grain size of their entire bulk masses. It suggests that for a given set of nearshore wave conditions and beach slope, an equivalence would exist between a smaller aragonite grain and a larger quartz grain. There is a two-fold consequence of the aragonite having a superior settling velocity per each grain fraction: 1) aragonite is less entrainable, that is, it is less likely to be cast into suspension than the quartz, and 2) when the aragonite and quartz are simultaneously suspended by breaking waves, it is hypothesized that aragonite would fall back into the bed matrix faster and thus experience less movement in suspension than the quartz. On a granular scale, it seems probable that due to the more rounded and spherical nature of the aragonite, it ought to possess a lower drag coefficient, a property that would enhance its ability to descend out of suspension.

In addition to settling velocity from suspension, the hydraulic equivalence of mineral grains may be a function not only of abundance and grain density but of the interaction between grains in their environment due to the relative differences in their sizes and shapes (McIntyre, 1959). Slingerland (1984) described a situation where the pre-existing coarse substrate is trapping a moving population, a scenario much like that in the present study where the mean sizes of the aragonite and quartz samples are approximately half of the host Lloyd Beach material. According to Slingerland (1984) the overall sorting mechanism in a placer-type deposit can be sub-divided into four processes: entrainment sorting, suspension sorting, shear sorting, and transport sorting.

Entrainment sorting is the separation of grains into distinctive populations of different size, density, and shape by differential pick-up off a bed. This is the mechanism most used to explain the characteristics of lag deposits, such as the distribution of aragonite and quartz remaining on the injection line upon completion of the present experiments. The important variables are friction velocity (U*), grain diameter (d), grain density (Rho), and bottom roughness (k). Essentially, for an initial fixed bottom roughness size (k), the critical frictional velocity that must be exceeded to achieve entrainment is high for grains much smaller than k due to sheltering effects (Slingerland, 1984). In the present study, the sheltering effects are probably greatest for the smaller, fall (settling) equivalent aragonite than for the larger fall equivalent quartz perhaps enhancing the "hiding" ability of the aragonite. This would agree well with the results of Slingerland (1977) in which finer, denser particles (i.e. aragonite in this thesis) were argued to be more difficult to entrain because they have larger reactive angles through which they must be rolled, and also because they project lower in the velocity profile than the surrounding roughness elements.

Suspension sorting is the fractionation of grains of different settling velocities into different levels off the bed in a turbulent, open-channel flow. Shear sorting describes separation into different horizons in the moving bed layer. These two mechanisms were not specifically applied to explain the local sediment movement in the experimental grids of this study.

Transport sorting (which actually contains entrainment and suspension sorting), as described by Slingerland (1984), is the fractionation of grains by differential transport. It is caused by variabilities in the probability of entrainment as well as in the motion and mean velocity of a grain already moving in the flow. The results of the present study show the aragonite to be more resistant to movement in the surf zone than quartz (Figures 31 through 34). Thus, there is a difference between transport equivalence and settling equivalence between these two materials, with the denser aragonite grains moving alongshore less rapidly than the fall equivalent quartz grains. These findings may in part relate to the difficulty of entrainment (Hand, 1967) of the smaller aragonite grains compared to the settling equivalent, larger and less dense quartz grains. In a similar study, Trask and Hand (1985) also showed that smaller, denser minerals are less transportable than larger, less dense, fall equivalent grains and concluded that the degree of deviation was a function of the mineral's effective-density ratio. This conclusion not only supports Rubey's (1933) belief that density was the dominant controlling factor in the principle of hydraulic equivalence but also explains why in the present study, the aragonite appeared to be much less transportable than the quartz despite similarities in their respective grain sizes.

The emphasis throughout this discussion has been on the smaller size fractions of the quartz and aragonite since this is where the mode, mean, and approximately 70-80% of the total mass of the aragonite and quartz is found. According to Winkelmolen (1971), the smaller the grains the more their shape (i.e. their surface area/weight ratio) becomes important to their dynamic behavior in water and air. Based on their grain size distributions, the test materials are much smaller than the inherent bed roughness on Lloyd Beach. It seems probable that because of the grain size distribution on Lloyd Beach, the manifestation of the bed load transport of aragonite and quartz is dampened due to the complexities in grain to grain interaction within the bed matrix. Bed load transport is an important factor in the larger size fractions (greater than 0.5 mm) as the grains that are being moved via traction and saltation become closer in size to the background bed roughness. It is believed that this process has had only a minor contribution to the total mass movement in the present study since the bulk of the aragonite and quartz by weight occurs in sizes much smaller than the background Lloyd Beach bed roughness.

The influence of grain shape in the overall transport process is very difficult to assess. In the smaller sizes where suspension transport is most important, it is apparent that rounded/spherical grains having smaller drag coefficients settle out of the water column faster and undergo less transport in suspension. The results of MacCarthy (1933) also support this hypothesis. The belief that rounder and more spherical grains should be better transported in bottom traction was contradicted by the results in Winkelmolen (1969). In that study, a good "rollability" proved to be unfavorable for transport in constant contact with the bottom, especially in those cases where the bottom roughness was equal to or slightly larger than the grain size of the transported material (such as the present study). Grains of low rollability (less rounded and less spherical) possess a high surface / weight ratio, which makes them more susceptible to the drag forces of the medium. Even more important, these less rollable shapes can sink less deeply into the interstices of the somewhat coarser but more evenly distributed bottom population grains (Moss, 1962). Thus, spherical and equidimensional grains of the same weight and density "feel" the bottom roughness more than the more angular, less equant grains. For the present study the implication is that on a grain-for-grain basis, the more rounded and more spherical aragonite is less "rollable" than the less rounded and less spherical quartz. Close examination of the larger grain sizes for aragonite reveals that as size increases above 0.50 mm, this material becomes less rounded and spherical and very much resembles the fragmented biogenic nature of the larger sized quartz and native Lloyd Beach sands. Newell et al. (1960) confirms this observation noting that although Bahamian oolitic aragonite tends to be spherical or ellipsoidal, grains are commonly found with so few lamellae that their shape reflects primarily the form of the nucleus and may be quite varied. It is hypothesized that because of this trend of decreasing roundness and sphericity with increasing grain size, the aragonite becomes similar in shape to the quartz sample and tends to respond in a hydraulically similar manner as the quartz. This finding closely parallels the observed decrease in density with increasing grain size for the aragonite and suggests that perhaps the influences of both shape and density are controlled by the relationship between the number of oolitic coatings (lamellae) and the initial grain nucleus diameter. The microphotographs in Figures 17 through 27 indicate that aragonite has the greatest proportion of oolitically coated grains in the size fractions less than 0.35mm. This would explain why the aragonite had a higher density and was much less transportable in the smaller grain fractions but existed in similar abundances as the quartz with increasing grain size. At approximately 0.35mm and larger, the tracer results show the individual quartz sizes actually experienced slower transport. It is believed that this occurs because in this size range these test materials are equal to or larger in grain diameter than the inherent bed roughness (k) of the beach. It was previously mentioned that the rounder, more spherical grains were less moveable in traction (bed load) when these grains were less than or equal to the background bed roughness. In the case of grains larger than 0.35mm, the bed roughness is exceeded, the interstitial sheltering effects are no longer present, and it is believed that the rounder aragonitic grains are actually more rollable than the more angular quartz -- a analogy similar to grains riding on top of the carpet rather than slightly below the surface.

In skeletal carbonate sands, the erosional velocities are only weakly correlated with grain size and do not correlate well with various shape factors (Young & Mann, 1985). Although the larger biogenic calcium carbonate fragments comprise a very small percentage of the total aragonite and quartz materials, some uncertainty exists as to their mode and magnitude of erosional transport. Due to the variability in shape and the fragmented nature of these larger calcium carbonate components, it seems likely that absolute size has the greatest influence in their transportability.

Shape is but one of the irregularities observed within most biogenic calcium carbonate beach sands. Considerable density variations also exist within these materials depending on the content of microscopic gas vescicles, structural inconsistencies during shell accretion, and percent aragonite versus calcite present in overall bulk composition. These effects are no doubt manifested differently for each of the three materials which adds to many uncertainties in the upper grain size classes. In the present study, for grain sizes greater than 0.30 mm, the quartz sample showed more stability in the surf zone, i.e. it was less transportable than the aragonitic grains of the same size. This trend is attributed to quartz being similar in shape, more uniform in density and crystal structure, and because the bulk density of the quartz in these larger sizes is greater than that of the aragonite.

The question remains as to how the concepts previously discussed relate to the two objectives in this study. When examining equal masses of aragonite and quartz, which material is less transportable ? And secondly, on an granular scale, what is controlling the transportability of these materials? In the first case it was found that when examining overall bulk masses, the aragonite sample was less transportable than the quartz (Figures 31 through 34). It is suggested that this is due to less preferential entrainment and greater suspension sorting of the aragonite in the grain sizes smaller than 0.35 mm where approximately 70% of the mass by volume occurs. Aragonite has a slightly larger cumulative grain size than the quartz as well as a demonstrated higher overall density, roundness, and sphericity. These qualities were most critical in determining relative grain movements in suspension load, where it is postulated the majority of transport in these sizes has occurred. Suspension transport was deemed most important since aragonite and quartz both have a mean grain size approximately half that of the inherent Lloyd Beach bed material, thus it is assumed these materials would have been subjected to substantial sheltering effects from bed load transport.

The second objective of this study was to determine how secondary properties such as density and shape influenced selective sorting on the beach. In these size classes 1.5 phi (0.35mm) and less, aragonite was a predominantly well-rounded, dense, chemical precipitate. The analogy to the sorting of heavy mineral beach placer deposits is most applicable in this case where hydraulic equivalence suggests that for two grains of the same size, the denser aragonite has a greater settling/fall velocity. Also, the deviation in transport equivalence from fall equivalence as demonstrated in previous studies suggests a further enrichment of the smaller, denser aragonite grains relative to the larger less dense fall equivalent quartz grains. The aragonite became more transportable as grain size increased from 2.0 phi to 1.0 phi (0.25-0.50mm). This is attributed to two factors: 1) the effective-density ratio between the quartz and aragonite approached one as aragonite assumed a more irregular biogenic nature, resembling the larger calcium carbonate component of the quartz sand in these size classes, and 2) the roundness and sphericity of the aragonite also decreased with increasing grain size, an observation that in previous studies suggests increased movement in both the suspension and bed load modes of transport.

Aspects of Beach Renourishment

All of the results in the present study suggest aragonite to be a superior renourishment material compared to a quartz sand of similar size, based on a comparison of their relative transportability in the surf zone. Willingham (1985) indicated the possibility of a breakdown in the soft, less durable aragonitic particles such as the coral fragments and cemented oolitic grains (aggregates) due to interparticle abrasion. Nevertheless, he considered the amount of breakdown to be insignificant and hypothesized that under favorable conditions the released calcium carbonate could precipitate as a natural cement. The natural adhesive qualities of aragonite were also documented be Cunningham (1966) who indicated that this property should provide greater resistance to erosion yet permit infiltration of seawater. Monroe (1969) conducted a laboratory wave tank study that compared the deformation of aragonite and quartz of the same hydraulic size distribution. The study concluded the oolitic aragonite is as good a beach renourishment material from a hydraulic standpoint as a quartz sand of the same hydraulic size. An economic evaluation by A.V. Strock & Associates (1984) indicated that the placement of aragonite would significantly reduce the offshore losses in the coastal area from Jupiter Island, Florida to Pompano Beach, Florida. The cost would be higher than for utilizing an offshore borrow source. Currently, the Broward County Beach Erosion Prevention District is conducting an economic evaluation for John U. Lloyd Beach State Recreational Area to assess the economic feasibility of using aragonite versus other local borrow materials to restore this beach.

The question arises - can the present and past findings on oolitic aragonite apply to the current beach conditions in John U. Lloyd Beach State Recreational Area? Coastal Planning & Engineering, Inc (1985) evaluated several alternate sand sources for the beaches in Broward County which included the aragonite and quartz samples that were tested in the present study. Their study suggested that although variations existed in the onshore-offshore movement of these materials, their rates of longshore movement were essentially equal. The results of the present study indicate that transport variability also exists in the longshore direction and that this aspect of sediment movement should also be included when estimating the erosional losses within the local nearshore sediment budget. The present study, which was based on aragonite having a mean grain size of 0.27 mm, predicts aragonite to be less erodible than a quartz sand of similar size. This finding supports the previous hypothesis suggested by Marcona Ocean Industries, Inc. that aragonite should actually be hydraulically similar to a larger sized quartz sand. Newell et al. (1960) stated that the median grain diameters of Bahamian oolitic aragonite ranged from 0.25-0.42mm, with minimum and maximum grain diameters of 0.13mm and 1.0mm respectively. This would imply that the present study characterized the transportability of the smallest materials from the Bahamian Islands. It is interesting to note that the most recent investigations (EQCB, 1987) found the same material to possess a much larger mean grain size from two source localities: 1) a composite from a mining stockpile which yielded a mean size of 0.52mm, and 2) a beach composite that averaged approximately 0.40mm in grain diameter. The previously mentioned studies by Willingham (1985), A.V. Strock & Associates (1984), and Monroe (1969) showed mean grain sizes for the oolitic aragonite in the range of 1.7-1.9 phi (0.27-0.31mm). Clearly the ability to predict beach losses of the aragonite depends on the true grain size of the material. Berg and Duane (1968) showed that renourishment requirements were substantially reduced from the utilization of sand fill that has a mean size larger to that originally found on the eroding beach. The principle of hydraulic equivalence suggests that because of aragonite's higher density and sphericity, perhaps a composite with a slightly smaller mean size distribution than that found on Lloyd Beach could be expected to behave similarly to the native material.

According to the Broward County Beach Erosion District (1987), an aragonite mining stockpile site on Ocean Cay (mean size 0.52mm) represents the most probable material that would be supplied by Marcona Ocean Industries if beach restoration were to be undertaken with aragonite. It is difficult to extrapolate the results of my study to the dynamic behavior of this stockpile aragonite on Lloyd Beach since the two aragonite samples varied considerably in mean size. However, it is common practice in beach renourishment projects to make a theoretical estimate of how compatible the borrow material is with the native beach to be restored. A criteria developed by the U.S. Army Corps of Engineers estimates the rate of erosion for a potential borrow material. The renourishment factor (R_J, U.S. Army Corps of Engineers, 1985) is the ratio of the rate at which a borrow material will erode to the rate at which the natural beach material is currently eroding. This theoretical coefficient depends strictly on mean size. As mean size increases, R_J decreases, theoretically providing a more stable beach. Thus, based on size alone, utilization of the stockpile material (mean size 0.52mm) which is larger than the current material on Lloyd Beach, should provide a more stable beach than currently exists in John U. Lloyd Beach State Recreation Area.

My results indicate that higher density material also reduces transportability. While the aragonite tested in my study (mean size 0.27mm) possessed dense oolitic coatings only in the smaller grain fractions, examination of the aragonite stockpile material (mean size 0.52mm), indicates that it maintains a laminated, oolitic nature (high density) throughout all of its grain size classes (EQCB, 1987) which should enhance its beach stability. If this stockpile aragonite is utilized to restore the beach in John U. Lloyd Beach State Recreational Area, the cost estimates should be much lower since in the long run much less material would be lost from the project site.

The results of this thesis suggest aragonite will perform very favorably as a beach renourishment sand. In order to refine the compatibility estimates of aragonite on Lloyd Beach, a sediment transport study should be done which utilizes larger quantities of this material and closely monitors beach changes over a longer time period. At that time the economic feasibility of restoring this beach should be addressed since it will be easier to predict its long term dynamic behavior.

VI. SUMMARY

An oolitic aragonite beach sand from the Bahamas and an equally sized quartz quarry sand from South Florida were evaluated as beach renourishment materials for John U. Lloyd Beach State Recreational Area in Dania, Florida. The following summarizes the findings in this study:

1) When testing equal volumes of aragonite and quartz of a similar mean grain size, the aragonite experienced slower transport in the longshore and in the onshore-offshore directions.

2) On an equal grain size basis, aragonite showed slower transport in the smallest grain fractions (0.35mm and less) whereas the quartz experienced less transport in the larger sizes (> 0.35mm). Since 70-80% of these materials by weight were in the size classes < 0.35mm, aragonite was less moveable in bulk volume. These same findings were documented for two separate experiments despite extremely different wind and wave conditions that existed at the time in both.

3) Density and shape play important roles in the entrainment and selective sorting of the aragonite and quartz in the surf zone. When the differences in density and shape were greatest, the difference in relative transport was also the greatest.

4) The principle of hydraulic equivalence is obeyed especially in the smaller grain sizes where the effective density ratio of the aragonite to quartz is greatest. There is also a deviation of transport equivalence from settling equivalence in the smaller fractions between the smaller aragonitic grains and the larger fall equivalent quartz grains (in agreeance with Trask and Hand, 1985) which further enriches the abundance of aragonite relative to the quartz.

5) In the smaller grain sizes, where suspension sorting is important, the aragonite has a greater settling velocity, falls out of suspension faster, and may be more difficult to initially entrain into suspension. Aragonite's superior roundness and sphericity gives it a larger reactive angle and permits it to sink lower in the velocity profile.

6) As grain size increases above 0.35mm, the quartz and aragonite samples approach the background bed roughness and bed load transport becomes important. For grains smaller than this roughness size and in constant contact with the bed, rounder grains are less preferentially transported, a situation that would further decrease the movement of aragonite in these smaller sizes. As grain size increases above the bed roughness, the grains in constant contact with the bottom roll continually on top of the bed which

may be why the aragonite experienced more transport relative to the quartz in these larger sizes.

7) With increasing grain size, the aragonite becomes less dense, less rounded, and less spherical which correlated well with increased transport rates. The relationship between aragonite's initial nucleus size and the number of oolitic lamellae appear to control the density, shape, and consequently the transportability of this material.

8) Additional transport studies should be initiated using larger quantities of material to be monitored over longer time scales. This should facilitate better predictions on the long term erosional behavior of aragonite in John U. Lloyd Beach State Recreational Area.

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Appendix A

Size distribution data for aragonite, quartz, and Lloyd Beach based on sieve analyses

SIEVE ANALYSIS DATA

Arag - B 7-9-86
Wt. of sample shaken = 31.52g
Wt. loss = 0.28g
Percent error = 0.89%
Split 4 times

Size(mm) (phi)	Wt. retained in screen (g)	Cum. Wt. (grams)	Wt. Percent each fraction	Cum.%
4.00 (-2.0)	0	0	0	0
2.80 (-1.5)	0.23	0.23	0.73	0.73
2.00 (-1.0)	0.30	0.66	0.95	1.68
1.40 (-0.5)	0.43	1.09	1.36	3.04
1.00 (0.0)	0.65	1.74	2.06	5.10
0.71 (0.5)	0.86	2.60	2.73	7.83
0.50 (1.0)	1.20	3.80	3.81	11.64
0.355 (1.5)	5.76	9.56	18.27	29.91
0.250 (2.0)	6.26	15.82	19.86	49.77
0.180 (2.5)	7.06	22.88	22.40	72.17
0.125 (3.0)	5.02	27.90	15.93	88.10
0.090 (3.5)	2.85	30.75	9.04	97.14
0.063 (4.0)	0.39	31.14	1.24	98.38
pan	0.10	31.24	0.32	98.70

Arag 7-2-86
Wt. of sample shaken = 40.76g
Wt. loss = 0.03g
Percent error = 0.07%
Split 4 times

Size(mm) (phi)	Wt. retained in screen (g)	Cum. Wt. (grams)	Wt. % each fraction	Cum %
4.00 (-2.0)	0	0	0	0
2.80 (-1.5)	0.17	0.17	0.42	0.42
2.00 (-1.0)	0.43	0.60	1.05	1.47
1.40 (-0.5)	0.35	0.95	0.86	2.33
1.00 (0.0)	0.92	1.87	2.26	4.59
0.71 (0.5)	1.09	2.96	2.67	7.26
0.50 (1.0)	1.46	4.42	3.58	10.84
0.355 (1.5)	7.83	12.25	19.21	30.05
0.250 (2.0)	7.89	20.14	19.36	49.41
0.180 (2.5)	9.23	29.37	22.64	72.05
0.125 (3.0)	6.66	36.03	16.34	88.39
0.090 (3.5)	3.87	39.90	9.49	97.88
0.063 (4.0)	0.69	40.59	1.69	99.57
pan	0.14	40.73	0.34	99.91

101 - B 7-3-86
Wt. of sample shaken = 37.17g
Wt. loss = 0.19g
Percent error = 0.51%
Split 5 times

Size(mm) (phi)	Wt. retained in screen (g)	Cum. Wt. (grams)	Wt. % each fraction	Cum.%
4.00 (-2.0)	0.50	0.50	1.34	1.34
2.80 (-1.5)	0.29	0.79	0.78	2.12
2.00 (-1.0)	0.34	1.13	0.91	3.03
1.40 (-0.5)	0.34	1.47	0.91	3.94
1.00 (0.0)	0.39	1.86	1.05	4.99
0.71 (0.5)	0.49	2.35	1.32	6.31
0.50 (1.0)	0.90	3.25	2.42	8.73
0.355 (1.5)	3.98	7.23	10.71	19.44
0.250 (2.0)	7.55	14.78	20.31	39.75
0.180 (2.5)	12.52	27.30	33.68	73.43
0.125 (3.0)	5.60	32.90	15.06	88.49
0.090 (3.5)	3.46	36.36	9.31	97.80
0.063 (4.0)	0.45	36.81	1.21	99.01
pan	0.17	36.98	0.46	99.47

101 - 6-30-86
Wt. of sample shaken = 47.41g
Wt. loss = 0.34g
Percent error = 0.72%
Split 4 times

Size(mm) phi)	Wt. retained in screen (g)	Cum. Wt. (grams)	Wt. % each fraction	Cum.%
4.00 (-2.0)	0.88	0.88	1.86	1.86
2.80 (-1.5)	0.28	1.16	0.59	2.45
2.00 (-1.0)	0.30	1.46	0.63	3.08
1.40 (-0.5)	0.28	1.74	0.59	3.67
1.00 (0.0)	0.32	2.06	0.67	4.34
0.71 (0.5)	0.46	2.52	0.97	5.31
0.50 (1.0)	1.07	3.59	2.26	7.57
0.355 (1.5)	5.47	9.06	11.54	19.11
0.250 (2.0)	10.23	19.29	21.58	40.69
0.180 (2.5)	16.63	35.92	35.08	75.77
0.125 (3.0)	6.79	42.71	14.32	90.09
0.090 (3.5)	3.76	46.47	7.93	98.02
0.063 (4.0)	0.47	46.94	0.99	99.01
pan	0.13	47.07	0.27	99.28

Lloyd - 7-7-86
Wt. of sample shaken = 46.06g
Wt. loss = 0.19g
Percent error = 0.41%
Split 13 times

Size(mm) (phi)	Wt. retained in screen (g)	Cum. Wt. (grams)	Wt. % each fraction	Cum.%
4.00 (-2.0)	0.17	0.17	0.37	0.37
2.80 (-1.5)	0.27	0.44	0.59	0.96
2.00 (-1.0)	0.80	1.24	1.74	2.70
1.40 (-0.5)	0.87	2.11	1.89	4.59
1.00 (0.0)	1.78	3.89	3.86	8.45
0.71 (0.5)	3.45	7.34	7.49	15.94
0.50 (1.0)	3.85	11.19	8.36	24.30
0.355 (1.5)	8.00	19.19	17.37	41.67
0.250 (2.0)	11.10	30.29	24.10	65.77
0.180 (2.5)	12.45	42.74	27.03	92.80
0.125 (3.0)	2.89	45.63	6.27	99.07
0.090 (3.5)	0.21	45.84	0.46	99.53
0.063 (4.0)	0.02	45.86	0.04	99.57
pan	0.01	45.87	0.02	99.59

Lloyd - CE 7-16-86
Wt. of sample shaken = 33.27g
Wt. loss = 0.12g
Percent error = 0.36%
Split 5 times

Size(mm) (phi)	Wt. retained in screen (g)	Cum. Wt. (grams)	Wt. % each fraction	Cum.%
4.00 (-2.0)	0.49	0.49	1.47	1.47
2.80 (-1.5)	0.80	1.29	2.40	3.87
2.00 (-1.0)	0.69	1.98	2.07	5.94
1.40 (-0.5)	0.89	2.87	2.68	8.62
1.00 (0.0)	1.95	4.82	5.86	14.48
0.71 (0.5)	2.99	7.81	8.99	23.47
0.50 (1.0)	3.14	10.95	9.44	32.91
0.355 (1.5)	8.24	19.19	24.77	57.68
0.250 (2.0)	7.80	26.99	23.44	81.12
0.180 (2.5)	5.31	32.30	15.96	97.08
0.125 (3.0)	0.80	33.10	2.40	99.48
0.090 (3.5)	0.05	33.15	0.15	99.63
0.063 (4.0)	0	0	0	0
pan	0	0	0	0

Lloyd - A   7-16-86
Wt. of sample shaken = 53.48g
Wt. loss = 0.05g
Percent error = 0.09%
Split 4 times

Size(mm) (phi)	Wt. retained in screen (g)	Cum. Wt. (grams)	Wt. % each fraction	Cum.%
4.00 (-2.0)	1.45	1.45	2.71	2.71
2.80 (-1.5)	0.63	2.08	1.18	3.89
2.00 (-1.0)	0.72	2.80	1.35	5.24
1.40 (-0.5)	1.42	4.22	2.66	7.90
1.00 (0.0)	4.26	8.48	7.96	15.86
0.71 (0.5)	7.45	15.93	13.93	29.79
0.50 (1.0)	6.10	22.03	11.41	41.20
0.355 (1.5)	9.20	31.23	17.20	58.40
0.250 (2.0)	8.87	40.10	16.58	74.98
0.180 (2.5)	11.09	51.19	20.74	95.72
0.125 (3.0)	2.17	53.36	4.06	99.78
0.090 (3.5)	0.07	53.43	0.13	99.91
0.063 (4.0)	0	0	0	0
pan	0	0	0	0

Appendix B

Tracer grain counts used to generate the sediment transport data for experiments 1 and 2

TRACER GRAIN COUNTS

Tracer Grains / 225 Examined
(Average of Triplicate Analyses)

Experiment 1

I-1

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	2.00	0.00
2.00	0.00	2.00	0.00
1.40	3.00	4.00	0.00
1.00	5.00	12.00	4.00
0.71	2.33	6.00	3.00
0.50	3.33	3.33	6.33
0.35	7.33	11.67	6.33
0.25	9.00	18.67	12.33
0.18	25.00	30.67	8.67
0.125	103.33	75.67	2.67
0.09	125.67	68.33	1.00

I-2

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	1.00	0.00	0.00
2.00	1.00	3.00	0.00
1.40	1.00	3.00	0.00
1.00	4.00	7.50	3.00
0.71	3.67	6.33	7.00
0.50	7.00	5.67	12.00
0.35	21.33	12.00	22.00
0.25	24.33	22.33	17.00
0.18	23.67	30.33	11.67
0.125	109.33	53.00	4.67
0.09	133.67	57.00	0.33

I-3

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	1.00	2.00	0.00
1.40	2.00	3.00	1.00
1.00	4.00	9.00	5.00
0.71	3.00	4.00	3.00
0.50	4.00	2.00	13.67
0.35	19.33	10.33	20.00
0.25	21.00	11.67	13.67
0.18	47.67	36.67	13.00
0.125	122.00	68.33	3.33
0.09	125.00	64.00	0.00

I-4

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	1.00	2.00	1.00
0.71	1.33	6.33	4.33
0.50	1.33	4.00	3.67
0.35	4.33	4.00	4.33
0.25	4.67	9.67	2.33
0.18	5.00	9.67	0.67
0.125	41.33	25.33	0.67
0.09	92.00	23.67	0.00

I-5

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	1.00
1.40	3.00	0.00	0.00
1.00	1.33	0.67	0.67
0.71	3.00	1.67	4.33
0.50	3.00	4.00	6.00
0.35	5.67	7.67	2.67
0.25	4.33	7.67	3.00
0.18	9.33	12.33	3.00
0.125	17.00	13.00	0.67
0.09	35.67	5.67	0.00

AN-1

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	1.00	1.00
2.00	0.00	0.00	0.00
1.40	1.00	0.00	0.00
1.00	3.00	0.00	2.00
0.71	0.33	0.67	0.67
0.50	1.00	0.67	2.00
0.35	1.00	0.33	1.67
0.25	1.33	0.67	2.67
0.18	4.67	1.00	1.00
0.125	34.00	20.33	3.00
0.09	56.67	28.33	0.00

AN-2

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	1.00	0.00	1.00
1.40	2.00	0.00	0.00
1.00	1.33	1.33	1.00
0.71	3.33	1.00	1.67
0.50	1.00	2.67	4.67
0.35	3.00	3.00	5.00
0.25	2.33	3.33	3.00
0.18	5.00	5.00	1.67
0.125	26.00	18.67	3.00
0.09	49.00	36.33	0.67

AN-3

Size(mm)	Arag	Qtz	Lloyd
4.00	1.00	0.00	0.00
2.80	1.00	1.00	0.00
2.00	0.00	3.00	0.00
1.40	2.00	4.00	0.00
1.00	4.00	8.00	7.00
0.71	3.00	4.00	6.33
0.50	5.67	5.00	11.67
0.35	21.00	8.00	29.00
0.25	20.33	7.67	17.33
0.18	35.00	21.00	15.00
0.125	75.00	38.00	5.67
0.09	161.00	45.00	0.00

AN-4

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	1.00	0.00
2.00	0.00	2.00	0.00
1.40	2.00	2.00	0.00
1.00	4.00	10.00	4.00
0.71	3.00	5.67	6.67
0.50	3.67	7.33	11.33
0.35	18.33	14.00	27.00
0.25	21.00	11.67	19.67
0.18	34.67	19.33	16.00
0.125	75.33	36.00	5.00
0.09	118.33	36.00	0.33

AN-5

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.00	0.00	0.00
0.71	1.00	2.00	4.00
0.50	1.67	5.33	4.67
0.35	7.00	7.33	8.67
0.25	6.67	9.67	8.67
0.18	15.00	13.33	3.67
0.125	25.67	22.33	1.33
0.09	74.33	36.67	0.33

BN-1

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.00	0.00	0.00
0.71	0.00	0.00	0.00
0.50	0.00	0.00	0.00
0.35	0.00	0.00	0.00
0.25	0.00	0.00	0.67
0.18	0.00	0.33	0.00
0.125	1.67	0.67	0.00
0.09	0.00	0.00	0.00

BN-2

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	1.00	0.00	0.00
1.00	0.00	0.00	0.00
0.71	0.00	0.00	0.00
0.50	0.00	0.00	0.33
0.35	0.00	0.67	1.33
0.25	0.00	0.00	0.33
0.18	0.33	0.67	1.00
0.125	4.33	1.67	0.33
0.09	0.00	0.00	0.00

BN-3

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0,00
1.40	0.00	1.00	1.00
1.00	0.00	1.00	0.00
0.71	1.00	0.50	1.00
0.50	0.33	1.00	1.00
0.35	1.33	0.67	2.00
0.25	2.00	3.00	2.67
0.18	3.67	1.67	2.33
0.125	17.67	11.33	2.00
0.09	79.00	41.00	0.33

BN-4

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	1.00	0.00
1.00	1.00	2.00	2.00
0.71	2.33	1.00	3.67
0.50	1.67	3.00	6.00
0.35	2.33	3.00	7.33
0.25	2.33	4.67	3.00
0.18	3.33	6.33	3.67
0.125	14.67	7.00	1.00
0.09	69.67	38.67	1.00

BN-5

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.00	0.00	0.00
0.71	0.00	0.50	0.50
0.50	0.33	0.67	1.33
0.35	0.33	0.33	1.33
0.25	1.00	0.33	1.00
0.18	0.33	0.00	0.00
0.125	2.67	4.00	1.00
0.09	21.33	11.33	0.33

AS-1

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.00	3.00	3.00
0.71	1.00	2.00	0.67
0.50	1.67	3.00	4.33
0.35	9.00	5.33	9.33
0.25	4.00	7.67	5.33
0.18	7.67	16.33	5.00
0.125	31.67	29.00	3.33
0.09	78.67	40.67	1.00

AS-2

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	1.00	1.00
1.00	0.00	2.00	0.00
0.71	0.50	3.00	2.50
0.50	0.00	1.67	2.67
0.35	2.67	1.00	2.00
0.25	2.67	3.33	1.00
0.18	2.33	4.33	0.67
0.125	16.00	12.00	2.33
0.09	29.67	12.67	2.00

AS-3

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	2.00	1.00
1.00	0.00	0.00	0.00
0.71	0.00	0.00	0.00
0.50	0.00	0.00	0.00
0.35	0.67	0.33	1.00
0.25	0.00	0.67	0.33
0.18	1.33	1.00	0.33
0.125	6.33	5.00	0.67
0.09	14.50	4.00	0.50

AS-4

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	1.00	0.00
1.00	0.00	0.00	1.00
0.71	0.00	0.00	0.00
0.50	0.00	0.00	0.00
0.35	0.33	0.00	1.00
0.25	0.00	0.00	0.00
0.18	0.33	0.00	0.00
0.125	1.00	0.33	0.33
0.09	6.50	3.50	0.50

AS-5

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.00	0.00	0.00
0.71	0.00	0.00	0.00
0.50	0.00	0.00	0.00
0.35	0.00	0.00	0.33
0.25	0.00	0.00	0.00
0.18	0.00	0.00	0.00
0.125	0.33	0.33	0.33
0.09	1.00	1.33	3.33

TRACER GRAIN COUNTS

Tracer Grains / 225 Examined
(Average of Triplicate Analyses)

Experiment 2

I-1

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.00	0.00	0.00
0.71	0.00	0.33	0.00
0.50	0.00	0.67	0.00
0.35	0.33	0.33	0.33
0.25	1.00	1.00	0.00
0.18	4.00	6.00	0.67
0.125	22.33	6.67	5.67
0.09	0.00	0.00	0.00

I-2

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	1.00	0.00
1.00	0.00	1.67	0.00
0.71	0.33	2.67	1.33
0.50	2.00	6.33	0.67
0.35	10.67	8.67	2.33
0.25	24.33	20.00	4.00
0.18	25.00	29.67	5.00
0.125	80.33	38.00	10.33
0.09	129.50	32.50	8.50

I-3

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.00	1.33	0.00
0.71	0.00	0.00	0.00
0.50	2.33	3.33	1.00
0.35	12.67	7.67	1.33
0.25	20.67	21.67	4.00
0.18	27.00	27.67	6.33
0.125	73.67	33.67	10.67
0.09	118.33	19.67	7.67

I-4

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.00	0.00	0.00
0.71	0.00	0.50	0.50
0.50	0.33	0.33	0.33
0.35	8.00	4.00	1.33
0.25	11.33	11.00	3.67
0.18	21.67	28.33	6.00
0.125	52.00	44.33	17.33
0.09	131.33	49.33	17.67

A-1

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	1.50	0.00	0.00
0.71	0.00	0.33	1.67
0.50	0.67	0.67	0.67
0.35	1.33	0.33	1.33
0.25	2.00	1.67	0.67
0.18	4.00	3.67	1.67
0.125	12.67	6.33	5.00
0.09	49.67	9.33	5.67

A-2

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	1.00	0.00
1.00	0.00	0.00	0.00
0.71	1.00	0.67	0.33
0.50	0.67	0.67	0.67
0.35	6.33	3.33	1.67
0.25	6.33	7.00	4.00
0.18	15.00	16.33	7.33
0.125	70.00	33.67	17.33
0.09	107.00	23.00	20.00

A-3

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.50	2.50	0.00
0.71	0.33	2.33	0.00
0.50	0.67	3.67	0.00
0.35	5.67	4.00	1.33
0.25	9.00	9.00	2.67
0.18	10.00	8.00	3.67
0.125	47.67	16.33	12.00
0.09	119.67	20.67	12.33

A-4

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.00	0.00	0.00
0.71	0.00	0.50	0.00
0.50	0.33	0.00	0.00
0.35	3.33	2.33	1.33
0.25	6.33	4.33	2.67
0.18	12.33	10.00	3.00
0.125	26.33	13.33	11.00
0.09	82.33	15.00	14.33

B-1

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	1.00	0.00
1.40	0.00	1.00	0.00
1.00	0.00	0.00	0.50
0.71	0.00	0.33	0.33
0.50	0.00	0.00	0.67
0.35	0.33	0.33	0.67
0.25	2.00	0.33	1.67
0.18	4.00	1.00	4.33
0.125	15.33	4.33	8.67
0.09	54.00	3.67	15.50

B-2

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	1.00
1.40	0.00	0.00	1.00
1.00	0.67	0.00	0.67
0.71	1.67	0.33	0.67
0.50	1.67	0.33	0.67
0.35	4.00	0.67	0.67
0.25	5.33	1.67	2.00
0.18	8.33	2.67	8.00
0.125	39.33	9.00	18.33
0.09	0.00	0.00	0.00

B-3

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0,00	0.00	0.00
1.00	0.50	0.50	0.00
0.71	0.33	0.00	0.00
0.50	2.33	0.00	1.00
0.35	4.67	0.67	2.33
0.25	5.33	2.00	2.33
0.18	14.67	5.00	5.00
0.125	38.00	8.67	14.00
0.09	0.00	0.00	0.00

B-4

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.00	0.00	0.00
0.71	0.00	0.00	0.00
0.50	1.67	0.00	0.33
0.35	2.00	0.00	0.67
0.25	1.33	0.67	0.00
0.18	2.33	1.67	0.00
0.125	5.67	1.67	5.33
0.09	28.00	6.00	6.00

C-1

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.00	0.00	0.00
0.71	0.00	1.00	0.00
0.50	0.00	0.00	0.00
0.35	0.00	0.00	0.33
0.25	0.67	0.33	0.00
0.18	1.67	0.33	2.00
0.125	10.67	1.00	6.33
0.09	36.00	5.00	15.00

C-2

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.33	0.00	0.00
0.71	0.33	0.33	0.33
0.50	1.33	0.00	0.00
0.35	3.33	0.00	1.33
0.25	5.33	1.00	1.67
0.18	10.33	2.33	4.00
0.125	35.50	4.00	16.00
0.09	0.00	0.00	0.00

C-3

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.00	0.00	0.00
0.71	0.67	0.00	0.33
0.50	1.33	0.00	1.00
0.35	3.67	0.00	1.33
0.25	6.33	1.67	2.67
0.18	12.33	2.67	4.67
0.125	58.00	4.00	26.00
0.09	0.00	0.00	0.00

C-4

Size(mm)	Arag	Qtz	Lloyd
4.00	0.00	0.00	0.00
2.80	0.00	0.00	0.00
2.00	0.00	0.00	0.00
1.40	0.00	0.00	0.00
1.00	0.00	0.00	0.00
0.71	0.00	0.00	0.00
0.50	1.67	0.00	0.33
0.35	3.33	1.00	0.33
0.25	0.67	0.33	0.33
0.18	1.33	0.33	0.67
0.125	3.00	1.33	2.00
0.09	20.50	3.50	7.50