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Bottom Sediment Mobility at the Wolf Trap Site in the Lower Chesapeake Bay

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Bottom Sediment Mobility at the Wolf Trap Site in the Lower Chesapeake Bay

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A Thesis
Presented to
The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
Of the Requirements for the Degree of
Master of Arts

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by
Mary M. Howard-Strobel
1989

APPROVAL SHEET

This thesis is submitted in partial fulfillment
of the requirements for the degree of

Master of Arts

Mary M. Howard-Strobel

Approved, August 1989

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Maynard M. Nichols

TABLE OF CONTENTS

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I thank my committee, Don Wright, John Boon, Bob Byrne, Bob Diaz, Woody Hobbs and Maynard Nichols for their advice and patience throughout the duration of this project. Sincere appreciation is extended to Linda Schaffner of VIMS and to Frank Bohlen of the University of Connecticut for their support and encouragement.

I am particularly thankful to my husband Charles Strobel who has also been a great source of understanding and support.

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

An assessment of the nature of the bottom mobility at Wolf Trap, a bay-stem plain environment of the Lower Chesapeake Bay, using textural parameters derived from grain size analysis indicates that the bottom sediments are dynamic and mobile. The methods of analysis of variance (ANOVA) and spatial autocorrelation were used to detect variations in the textural parameters with time and space. The results from the ANOVA analysis revealed a significantly higher silt to clay ratio for the surface sediments (0-5 cm) in the summer, compared to the winter, suggesting different processes may be dominating at different times of the year. Such processes include increased biological activity, seasonal discharge from the western shore tributaries, the winter crab dredge fishery, biological "rain" from the water column, and storm events. Spatial autocorrelation analysis provided further insight as to which processes may be influencing the bottom sediment texture. Correlograms produced from the autocorrelation analysis documented the existence and variation of spatial patterns with time and depth at Wolf Trap. Interpretation of the silt-to-clay-ratio correlograms support dominance of biological activity in the summer. These findings, in combination with results from previous investigations at the site, suggest that the bottom benthic regime is dynamic on at least seasonal time scales.

Bottom Sediment Mobility at the Wolf Trap Site in Lower Chesapeake Bay

INTRODUCTION

Sediment transport models have become common tools for predicting the modes, pathways, sources and sinks of hazardous materials, sewage waste, and dredged material disposed of in the estuarine environment. These models can be tailored to a wide range of conditions and sediment types. Sediment movement can be determined just as easily at a beach as it can be deep within a channel. All transport models require information about the sediment geotechnical properties (*e.g.*, size, shape, density), hydrodynamic conditions, and bottom characteristics (bedforms, bed shear stress). One of the more elusive, and critical, parameters is the bed shear stress, τ_b, which cannot be measured directly *in situ*, but is typically derived from velocity profiles (*e.g.*, Sternberg, 1972). Sediments will move whenever the bed shear stress reaches a threshold value for eroding the bed, the critical shear for erosion, τ_e. A stable, or non-mobile, bed will have a relatively high τ_e, while an unstable, or mobile, bed will have a lower τ_e. Thus, determining bottom sediment mobility is an important first step in establishing the sediment dynamics of a region and is essential to the accurate prediction of sediment movement in transport models.

Several recent studies have examined a particular region of lower Chesapeake Bay, known as Wolf Trap, as a result of the area having been designated as a dredged material disposal site (Diaz *et al.*, 1985, Boon *et al.*, 1987, Wright *et al.*, 1987, Schaffner *et al.*, 1987). These studies have examined different sedimentological aspects of Wolf Trap, yet no clear conclusions can be drawn about the nature of bottom sediment mobility. Byrne *et al.* (1982) described the sedimentary environment of Wolf Trap as primarily depositional, with total sand, silt and clay deposition on the order of 1-2 m-tons/m^2 /century. In an intensive benthic baseline monitoring survey a few years later, evidence was found suggesting both stable and unstable bottom types (Diaz *et al.*, 1985).

Wright *et al.* (1987) defined the Wolf Trap region as flat and featureless, and smooth across most spatial scales of bottom roughness discernable from side-scan sonagraphs. The exception was small-scale ($<$ 1 meter) biological roughness elements which were prevalent throughout the region. Roughness characteristics distinguish sediments on the basis of their potential mobility, *i.e.*, a rougher bed may indicate a more easily resuspended bottom due to increased local turbulence. However, if the roughness elements are densely distributed, the form drag component of the total shear stress is increased, the skin friction component becomes insignificant and sediment movement may actually be inhibited, thus stabilizing the bed (Nowell and Church, 1979; Nowell *et al.*, 1981). The effect of the biological roughness elements on sediment mobility at Wolf Trap is subject to this uncertainty.

The purpose of this study is to examine sediment characteristics in the Wolf Trap region of lower Chesapeake Bay and attempt to resolve the degree of bottom mobility as manifest by textural parameters.

Background on the Region and Study Site

The Wolf Trap study site is within the Virginia portion of Chesapeake Bay situated on the Atlantic Coastal Plain of the Eastern United States (Figure 1). Chesapeake Bay is a drowned river valley estuary, formed during the latest rise in sea level approximately 11,000 years ago. The width to depth ratio of the Bay is 300 to 1, analogous to a flat, shallow pan incised by a narrow and deep groove (Wolman, 1968). The Bay's circulation has been classified as partially mixed, with oscillating tidal currents being the most obvious circulational pattern (Pritchard, 1968). Salinity varies longitudinally from near normal seawater at the mouth to freshwater at the head, approximately 300 kilometers away. Wolf Trap lies near the western shore in the lower half of Chesapeake Bay, between the York and Rappahannock Rivers, and has an average depth of 12 meters.

Early sedimentological studies of the lower Bay were concerned with charting the general patterns of sedimentation. Ryan (1954) sampled 209 stations from the entire Bay and found that finer grained sediments were associated with the deeper regions, and sands were generally restricted to the shallow areas. Shideler (1975) sampled 200 stations in the southern half of the Bay and also concluded that there was a depth dependant variation in sediment texture; coarse sands were found in the wave-dominated shallows, whereas, muds and fine sand were associated with deeper tide-dominated channels and margins.

As part of a much larger Bay-wide study, Byrne *et al.* (1982) collected over 2000 sediment samples in the lower Bay. This resulted in the definition of

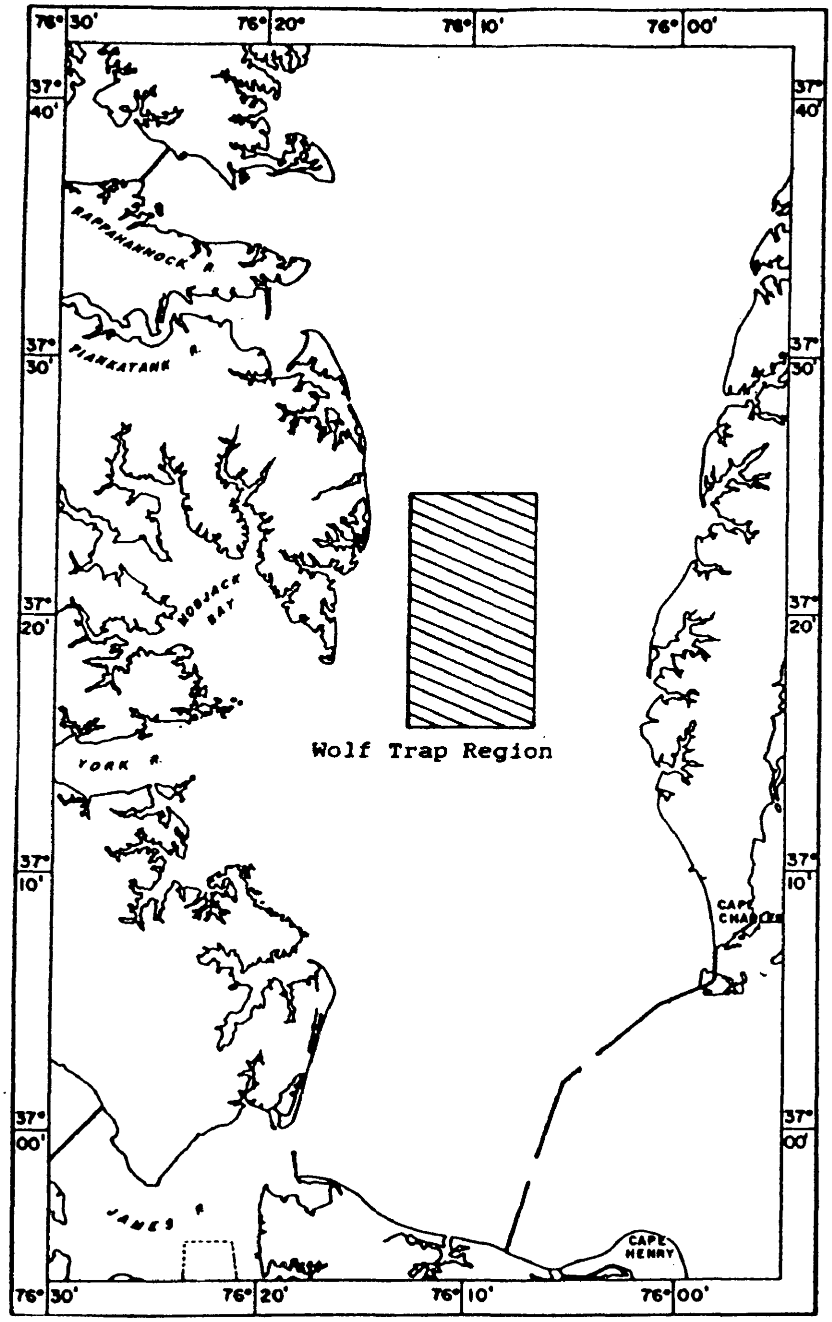


Figure 1. Location of the Wolf Trap Region in lower Chesapeake Bay.

sedimentation patterns at the highest resolution yet made in the Chesapeake Bay. They found the overall sediment composition to be sandier than in the previous investigations with appreciable net deposition of fine sands in the Wolf Trap region, suggesting considerable transport of fine sands from the Bay mouth to Wolf Trap, a distance of approximately 35 kilometers. The authors believed such transport is possible due to up-Bay bottom water circulation along the eastern shore in one of the deeper channels. The study gave an estimate for the mass accumulation of sand, silt and clay in this region as approximately 2 m-tons/m^2 /century.

Wolf Trap was designated a potential dredge material disposal area by the Army Corp of Engineers and a baseline monitoring survey of the sedimentology and benthic ecology was initiated (Diaz *et al.*, 1985). The study found that the sediment composition was sandier toward the eastern side of the site. The increased mud content on the western side was attributed to the many sub-estuaries providing muddy source sediment, and the larger cross-Bay gradient of depth varying sediment texture. An interesting note to the survey was the discovery of an anomalous sand patch (sand content greater than 70%) near the middle of the site.

Sediment profile camera imagery also demonstrated that the bottom at Wolf Trap appeared unstable, as revealed by the presence of surface mud clasts, shell lag deposits, bedform structures and exposed worm tubes. However, analyses of the surface sediment composition suggested a stable bottom, changing very little, if at all, over time, a postulate that is supported by a previous study of the region (Byrne *et al.*, 1982). Figures 2 and 3 are ternary diagrams, for the surface and subsurface layers respectively, of the percent weight of sand, silt and clay showing qualitatively the unchanging compositional nature of the region.

The biological results of the 1985 survey revealed a very diverse and abundant benthic community, suggesting a mature advanced successional stage community. However, during the study period, the authors noted a strong monotonic decline in total population abundances. There was also a gradient in faunal assemblages across the east-west sediment gradient. Sediment profile camera images revealed well-developed biogenic structures and evidence of a seasonally fluctuating redox potential discontinuity (RPD) with a maximum depth in August of 20 cm and a minimum depth in October and February of 4 cm. The authors concluded that the benthos was the major force affecting the physical structure of the surface sediments.

Wright *et al.* (1985) began an investigation of the benthic boundary layer within the lower Bay using side-scan sonar. Wolf Trap was described as flat and featureless, a baystem plain. A later survey by Wright *et al.* (1987) associated roughness factors with these bottom types which resulted in the classification of Wolf Trap as Type IIIa, virtually smooth across all spatial scales of bottom roughness except for small-scale biologically distributed roughness elements. These biological elements are characterized as having a vertical height of 1 - 10 cm and horizontal wavelength from 1 - 50 cm (Table 1).

The hydrodynamics of the region have not been intensively studied. Boon *et al.* (1987) proposed that gravity waves in the baystem plains do not significantly

Figure 2. Ternary diagram for the percent composition by weight of sand, silt and clay in the surface (0-5 cm) layer.

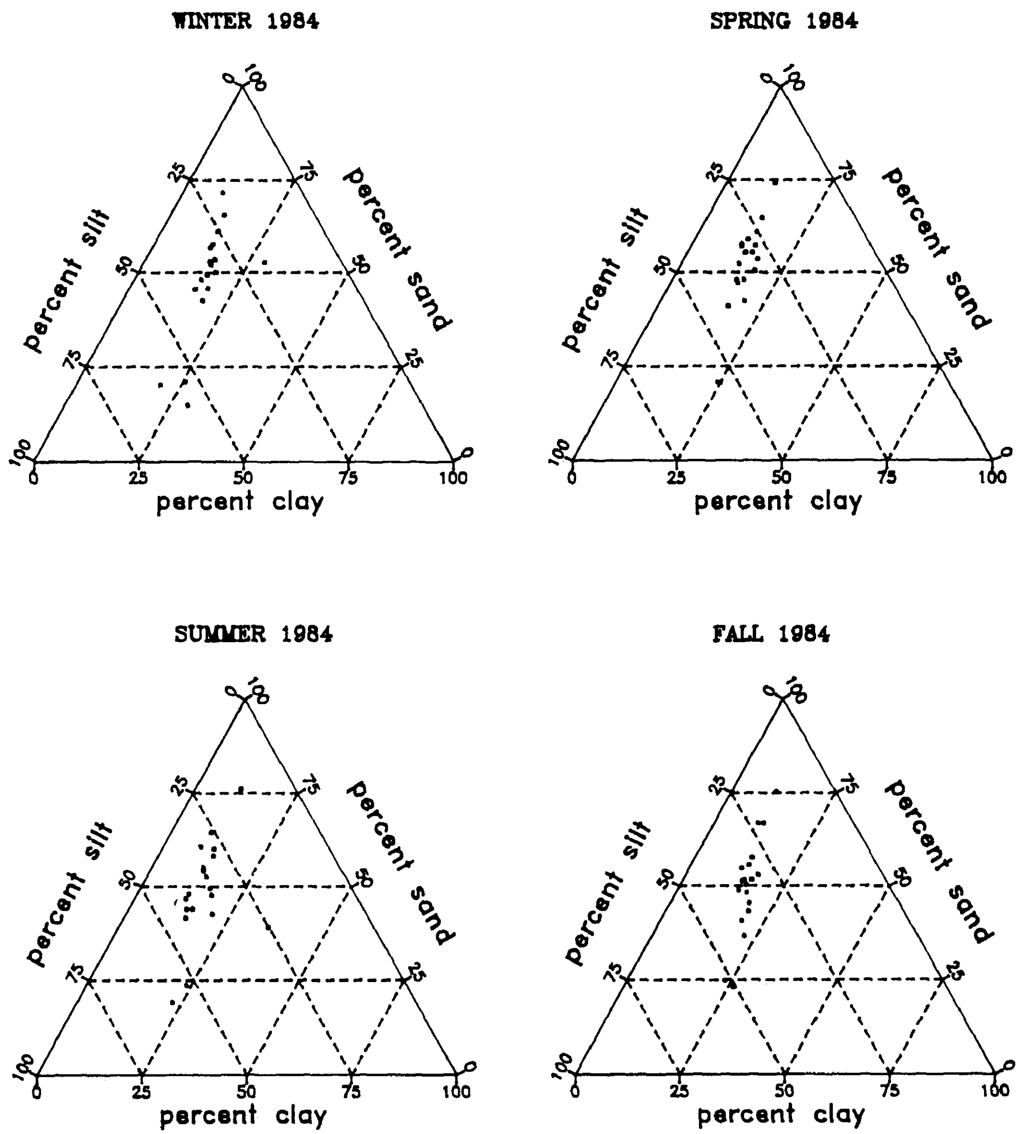
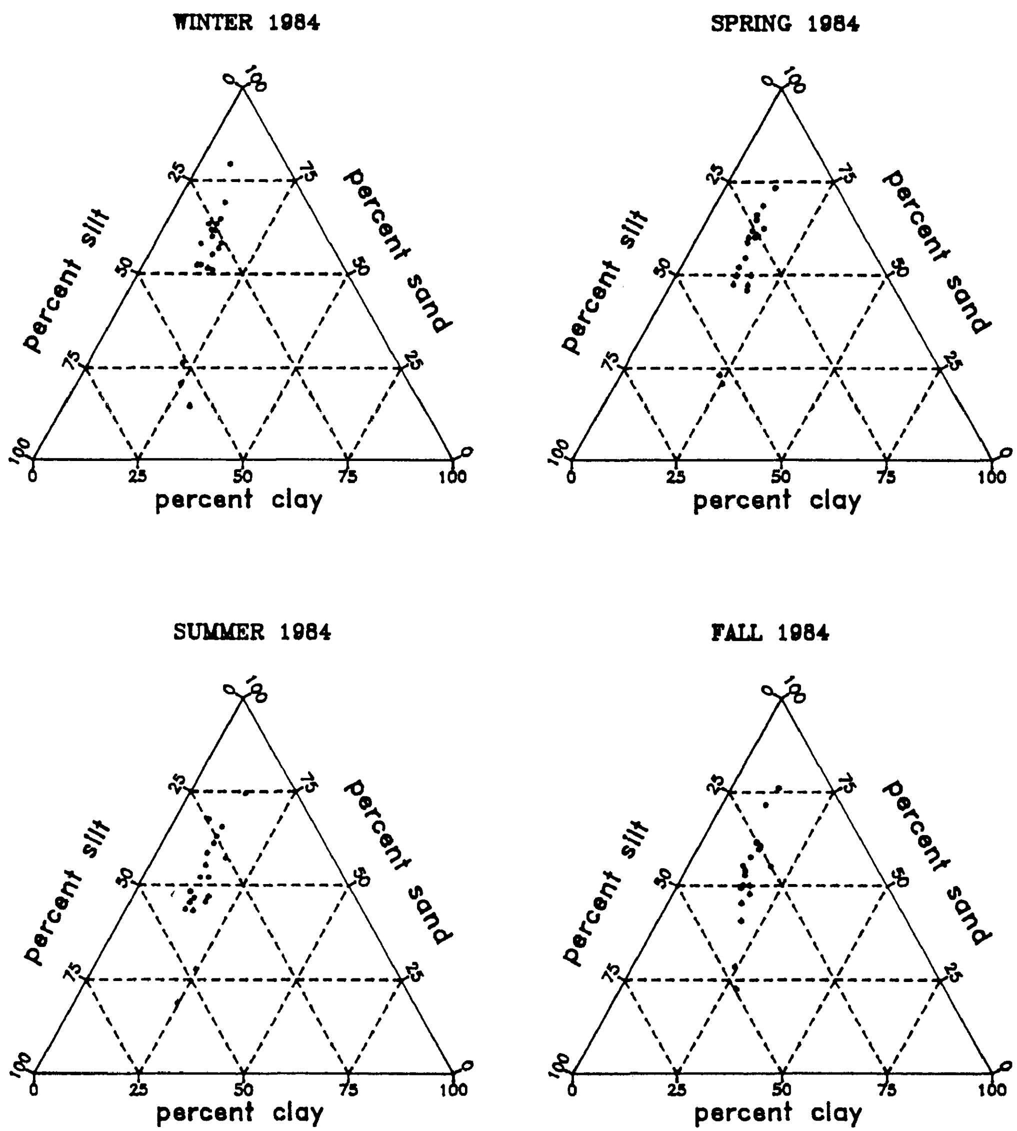

WINTER 1984
SPRING 1984
SUMMER 1984
FALL 1984
percent sand
percent silt
percent clay
0
25
50
75
100

Figure 3. Ternary diagram for the percent composition by weight of sand, silt and clay in the subsurface (5-15 cm) layer.



WINTER 1984
SPRING 1984
SUMMER 1984
FALL 1984
percent silt
percent sand
percent clay
0
25
50
75
100

affect the bottom, however, internal waves, with periods on the order of 50-100 seconds, may disturb and resuspend sediments. The authors suggest that the forcing of these high energy internal waves is related to such factors as extreme spring tides and stratification, thus, resuspension events may not always be tied to major storm events (*i.e.*, winter nor'easters or summer hurricanes), but could be occurring during times of the year previously thought to be uneventful. Current meter measurements have yielded estimates of maximum bottom velocities (measured at 20 cm above the bed) between 20 - 45 cm/sec amid the strong turbulent fluctuations possibly generated by internal waves (Boon *et al.*, 1987).

Table 1. Wolf Trap bottom types and roughness characteristics. Z_r refers to the vertical roughness size and wavelength refers to the horizontal wavelength (from Wright *et al.*, 1987)

Bottom Type	IIIA
Subenvironment	Baystem plain
Nikuradse roughness (Zr is a function of grain size; wavelength < 1 cm)	**smooth**
Small-scale distributed roughness (order Zr = 1-10 cm; wavelength = 1-50 cm)	Biological: **rough** Current induced: **smooth to medium** Wave induced: **smooth**
Meso-scale distributed roughness (order Zr = 0.1-2 m; wavelength = 0.5-50 m)	Biological: **smooth** Current induced: **smooth**
Large-scale bed morphology (wavelength > 50 m)	Flat, relatively featureless plains

HYPOTHESIS and OBJECTIVES

The primary objective of this study is to resolve the degree of mobility of the bottom sediments in the Bay-stem plains environment of lower Chesapeake Bay. The data set to be used contains physical information describing the textural characteristics of sediments over time and space from the Wolf Trap region. Observations of the change in sediment characteristics with time and space should provide an indirect, but accurate, means by which to achieve this objective. As sediments erode and are deposited, the sediment character may change due to processes such as winnowing, increases or decreases in biological activity, fluctuations in the rate of supply of source sediment or a change in the origin of source sediments. If the bottom is unstable, temporal or spatial changes in textural properties would be expected. A stable bottom would yield little change in textural parameters. Questions to guide investigation into changing properties can be posed as follows:

1 - Do sediment characteristics vary with time?

2 - Do sediment characteristics vary spatially? If so, do the spatial patterns vary with time, or, remain the same?

3 - How does the sediment character below the surface compare with that at the surface through time and space?

One would expect, from the background synthesis of information, that if the biota affect the physical structure of the sediments and the hydrodynamics suggest turbulent processes acting to disturb and resuspend the bottom, there should be some distinction in sediment character from one season to the next and with depth beneath the surface. Consequently, one would also expect changes in the associated spatial patterns of sediment character. If these expectations prove to be true, it would appear that conditions at Wolf Trap, and possibly other bay-stem plain environments, favor mobility, *i.e.*, frequent resuspension and deposition events.

METHODS

A) Data Set

The data used in this study comprise a subset of the database generated by Diaz *et al.* (1985) in a baseline monitoring investigation of the Wolf Trap site for the U.S. Army Corp of Engineers. That study sampled a minimum of twenty-one stations on a quarterly basis for one year. Nineteen stations were consistently sampled throughout the year and are used for this investigation (Figure 4). Station WTC02 was relocated after the winter sampling cruise for purposes beneficial to the original benthic survey. The data for this station were retained in the analyses to see how the different analyses would handle the position change, *i.e.*, what did the change do to the data and would the analyses be sensitive to the relocation? The dates of collection were February 1 - 10, March 30 - April 10, August 6 - 16, and October 29 - November 7, 1984. A U.S. Navy spade box corer with a surface area of $0.06m^2$ and a maximum depth of penetration of 60 cm was used to take two to four box cores at each station. Each box core was sectioned at 5 cm and 15 cm below the surface. A subsample of the sediment was extracted from each layer (0-5 cm and 5-15 cm) for grain size analysis and organic carbon content analysis. These samples were taken back to the lab and pooled for processing according to the standard methods for each

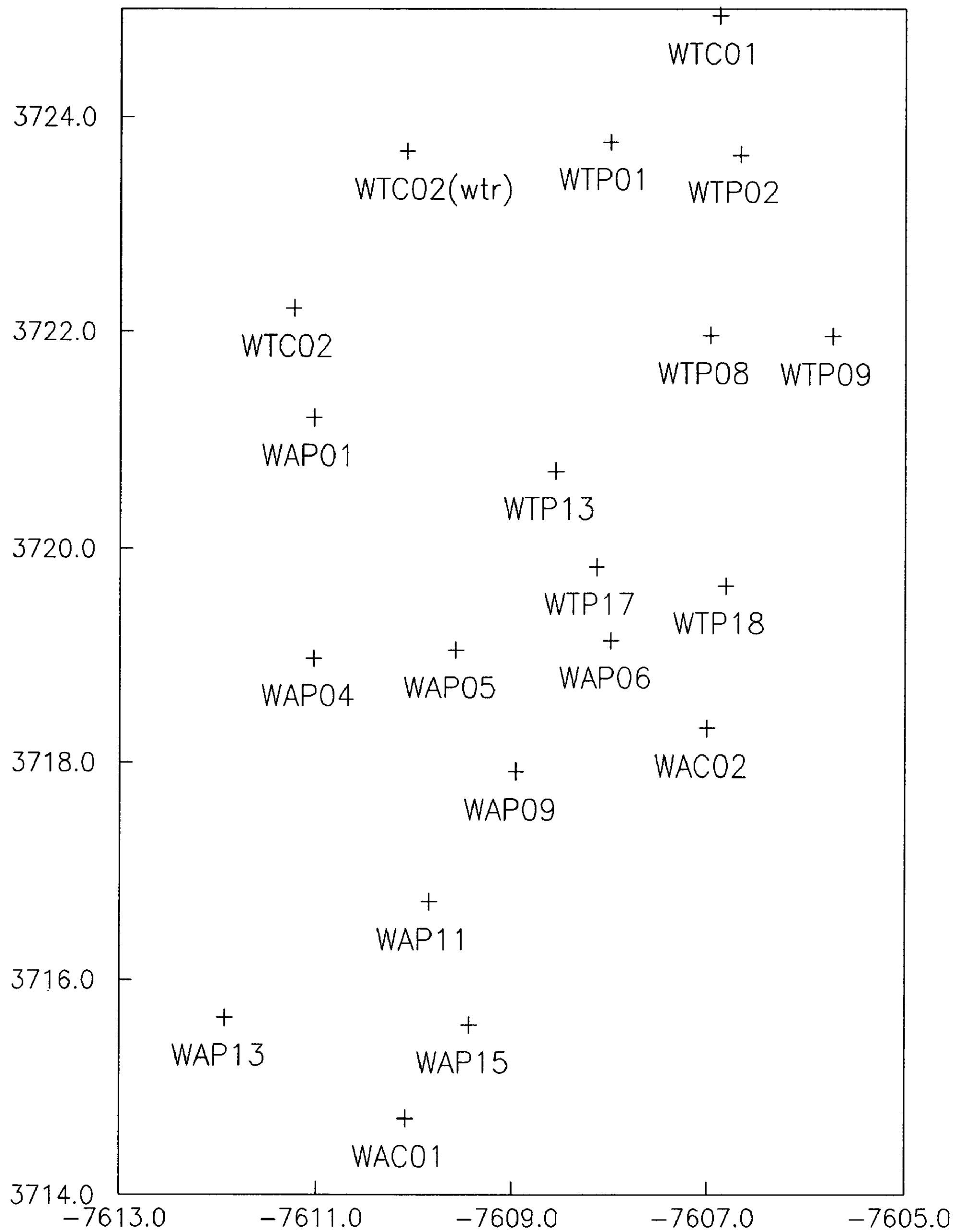


Figure 4. Location of the nineteen stations within the Wolf Trap study area. The relocated station, WTC02, is shown twice. The winter location is noted with "(wtr)".

type of analysis (see Diaz *et al.*, 1985, Part III, pp 41-52). Of the parameters that were measured during the study, four were selected for use in this analysis: weight percent sand, silt to clay ratio, organic carbon content and mean grain size. Isopleth maps of these four variables at the 19 stations were generated to aid in the analyses. Surfer™ Version 3.0, a mapping and contouring program for personal computers was used to produce the plots. The regional variable theory technique of Kriging was the algorithm used by Surfer™ to generate the contours.

B) Statistical Analysis

Two statistical techniques were selected for use in determining changes in sediment characteristics with time and space. To detect seasonal changes and differences with depth in the four textural parameters, Analysis of Variance was used. Detecting seasonal changes in spatial variability of textural parameters in the surface and subsurface sediment required the use of spatial autocorrelation techniques.

The first technique, Analysis of Variance (ANOVA), is a commonly employed method for detecting the significance of differences among means of a variable that has been collected from different groups or classes. As it applies to this study, the method was used to detect differences in weight percent sand composition, mean grain size, organic carbon content, and silt to clay ratio, from one season to the next and from the surface layer to the subsurface layer. A two-way, fixed effect Model I ANOVA was used. The ANOVA analyses for this study came from Statgraphics(TM) Version 2.6, a statistical software package for personal computers.

The second statistical method used in this study is spatial autocorrelation. Spatial autocorrelation has its founding in evolutionary and ecological fields (Whittle, 1954), but was later fully developed for use in analytical geography and demography (Cliff and Ord, 1973). The method tests for the dependence of a measure of a variable at one location to another measure of the same variable in a different location, providing a means by which to quantify spatial variability. Moran's I and Geary's c are two coefficients used to calculate spatial autocorrelation of interval or ordinal type data. The difference between these two measures is subtle; Moran's I will be most sensitive to the degree of departure of variate values from their mean, while Geary's c will depend on the absolute difference between the values. The degree of autocorrelation calculated by Moran's I and Geary's c are very similar (Sokal and Oden, 1978); as Moran's I is more common, it will be the coefficient used in this analysis.

The generalized form for Moran's coefficient I is as follows:

$$I = n \sum_{i \neq j}^{n} w_{i,j}\, z_i\, z_j \,/\, W \sum_{i=1}^{n} z_i^2$$

where n is the number of data points, w is a weighting matrix for the data set, z_i and z_j are the deviations from the mean for the ith and jth point in the data matrix, and W is the sum of all weighting coefficients $w_{i,j}$. Moran's I varies from +1 to -1, the expected value approaching zero in the absence of autocorrelation. Positive values indicate that similar values are adjacent (homogeneity), while negative values signify that dissimilar values are adjacent (heterogeneity).

The significance tests for either coefficient can be computed under two assumptions about the population from which the samples were drawn. The n (n = number of localities) variate values can be considered a sample from an infinite, normally distributed population (normality assumption) or, no assumption is made about the population and all possible permutations of the autocorrelation coefficient from the observed values for all localities is tested (randomization assumption). Sokal and Oden (1978) state that there is little difference between the two assumptions and that the randomization approach is more reasonable for most systematic applications; both are calculated in this study, but only the results for the randomization assumption were analyzed.

Part of the purpose of this study is to look for spatial patterns and to determine how these patterns may be changing with time; to achieve this objective, the spatial autocorrelation coefficient is calculated as a function of changing interpoint distance. The coefficient can be plotted against the distance classes, creating a correlogram. The correlograms provide information on the existence of spatial patterns and summarize the geographic variation exhibited by the data, providing a means by which to quantify spatial variability.

Figure 5a-d show examples of ideal correlograms for a data set that has been artificially generated and manipulated to simulate distinct spatial patterns (Sokal and Oden, 1978). A cline, or gradient, (Figure 5a) displays a gradual decline with increasing distance class. The interpretation is that as the distance class increases, differences between stations that are ever increasing distances apart are more dissimilar. An intrusion, *e.g.*, a patch of low variate values surrounded by a periphery of higher values with a sharp boundary between the regions, is shown in Figure 5b. The correlogram displays homogeneity (positive autocorrelation) at the lower distance classes when comparisons are being made within the patches. As the distance class increases, more comparisons are made between the central low value patch and the outer high value periphery, the autocorrelations become negative (heterogeneity). At the highest distance classes, i.e, those that roughly correspond to the diameter of the periphery, comparisons of variate values are made across the central patch, from one side of the periphery to the other; the resulting correlations become positive.

Figure 5c is what Sokal and Oden (1978) describe as a "crazy quilt" correlogram. High and low values alternate at regular intervals as the distance class increases. Such a pattern is suggested to be representative of a distance-dependant generating mechanism. A depression (Figure 5d) is essentially a circular cline with gradual gradients, and exhibits a correlogram similar to that of a regular cline. The lowest negative correlation indicates the approximate radius of the depression. Unlike the cline (Figure 5a), correlations do not continue to decline at the higher distance classes because the variate values are not as disparate.

The procedure used is based on an algorithm by Henley (1976). For irregularly spaced data points, the Euclidean distance matrix is taken and a weighting matrix is developed where all points within an interpoint distance class are given a weight of one, and all other points a weight of zero. For this investigation, eighteen distance classes were established for the Wolf Trap area, each distance class representing an increasing interpoint distance range of 500 meters, *i.e.*, 0-500 meters, 500-1000 meters, 1000-1500 meters, etc., up to a maximum interpoint distance of 9000 meters. Because the weights used were binary, an inherent assumption was that the data were isotropic and, therefore, no information was obtained about the directional properties of the spatial patterns. This is the simplest case of a weighting matrix and determines the existence of spatial patterns and whether or not they persist with time. The weighting matrix can be modified in subsequent analyses after any further characteristics about the data set have been revealed, *e.g.*, the weights can be distance-corrected or directionally-corrected or both, essentially fine-tuning the correlograms.

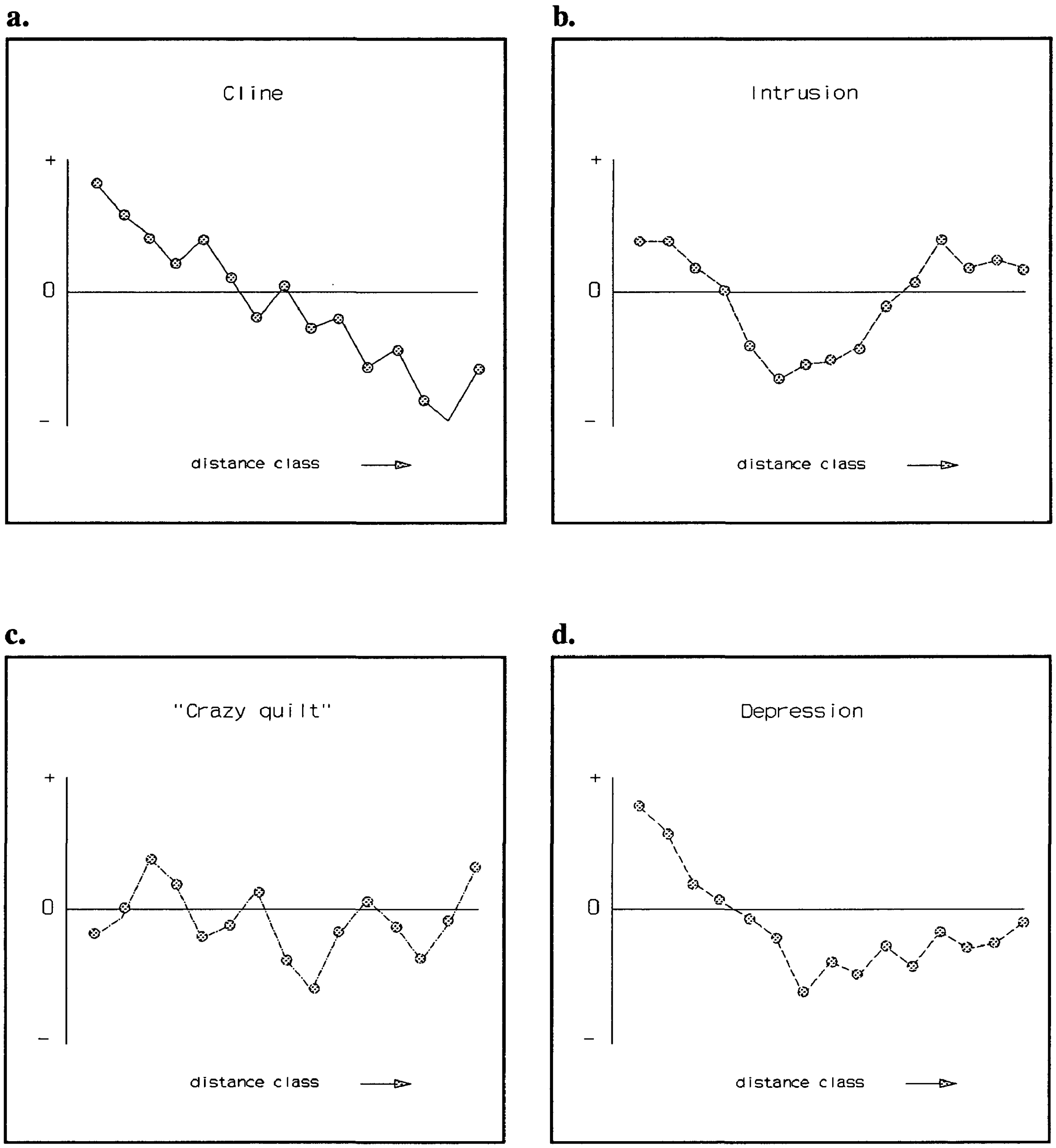


Figure 5a-d. Spatial correlograms resulting from a data set artificially generated and reshuffled to simulate different spatial patterns, a.) a cline, or gradient, b.) an intrusion, c.) a "crazy quilt", d.) a depression. See text for explanations. (from Sokal and Oden, 1978).

RESULTS

A) Isopleth Maps

Figures 6 - 9 show the surface (0-5 cm) isopleths of the four variables (% weight sand content, organic carbon content, silt to clay ratio and the mean grain size) for each season. The relocation of station WTC02 after the winter sampling survey had a marked effect on the contour patterns for the remaining three surveys. As mentioned previously, this station was retained to see how the different analyses would handle the relocation. The station relocation was not apparent in the ternary diagrams (Figures 2 and 3), but has been easily detected in the isopleth maps. The station was moved into an area of relatively high sand content and larger mean grain size. The contour maps for the percent sand content and mean grain size (Figures 6-7) are similar, displaying a west to east gradient of increasing sand content and grain size for the winter survey. The spring, summer and fall surveys display the same gradient, but a patch of sandier sediments is superimposed in the northwest corner of the area as a result of relocating the one station.

The winter silt to clay ratio isopleth maps (Figure 8) also display an eastward decrease in the silt content, however a sharp depression in silt content occurs in the southern region. The spring, summer and fall plots are quite

Figure 6 a-d. Isopleth maps of percent weight sand content in the 0-5 cm sediment layer for each season. The horizontal and vertical axis display the longitude and latitude, respectively, in degrees, minutes and tenths of a minute (*e.g.*, 3716.0 represents 37° 16.0")

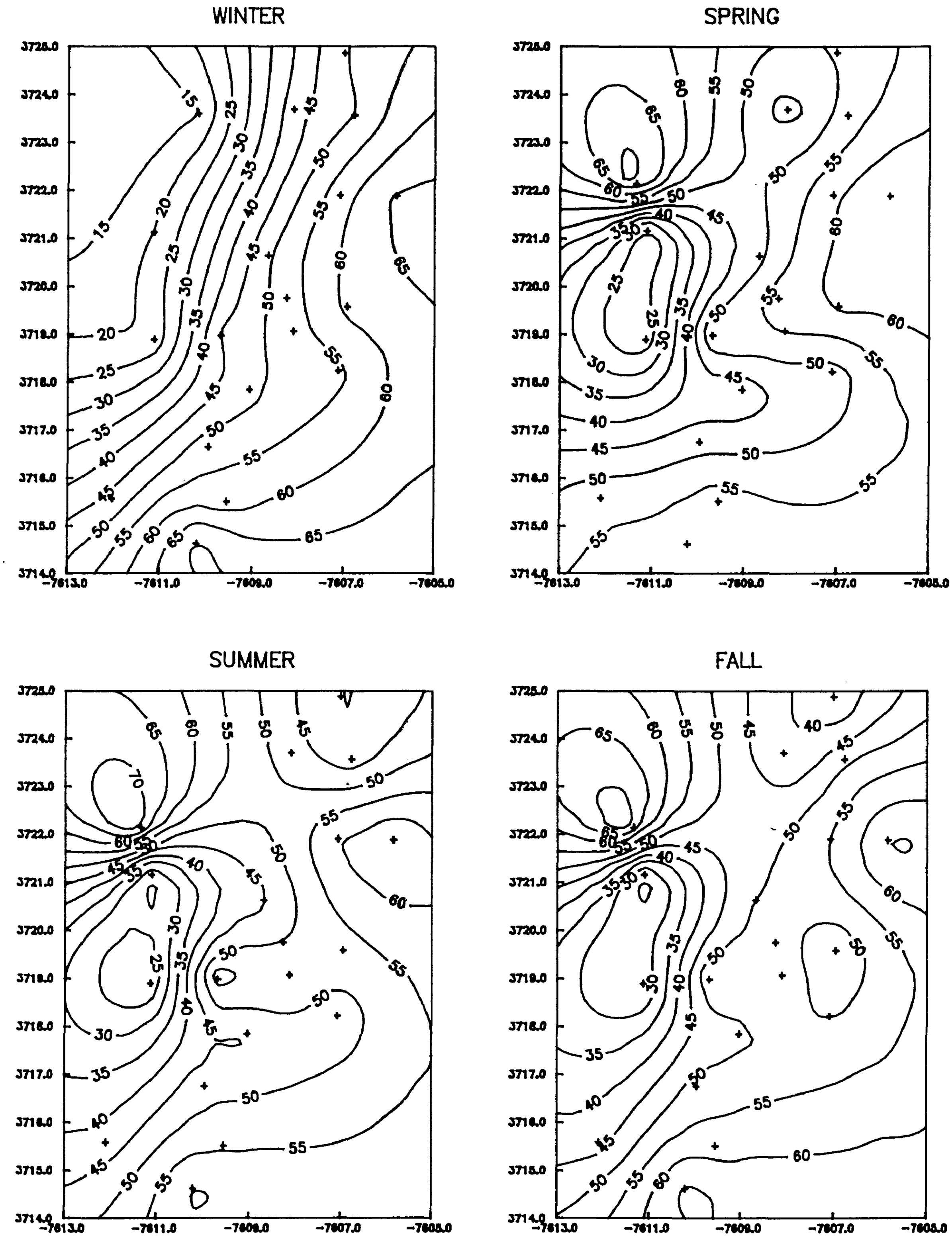
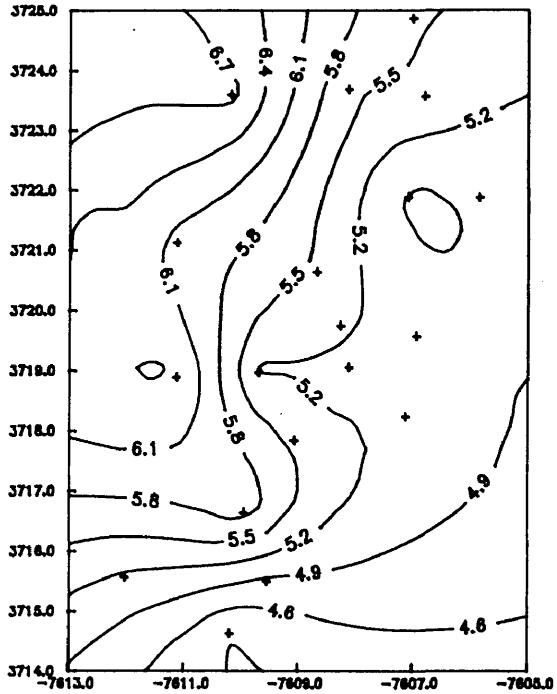
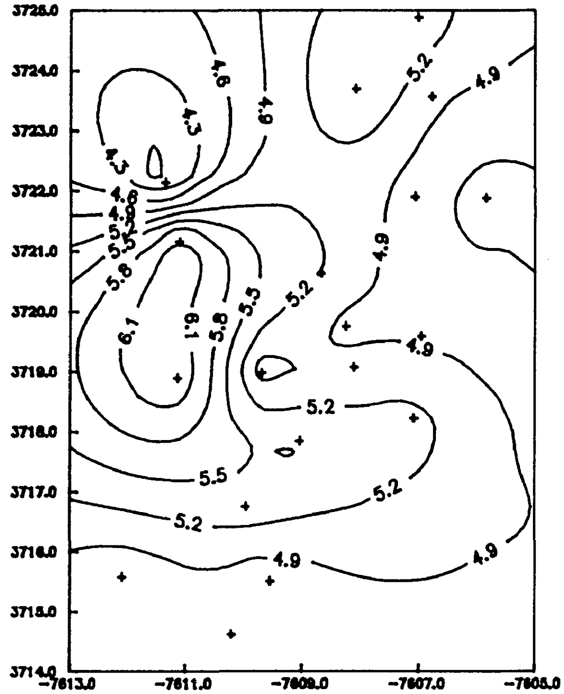

WINTER
SPRING
SUMMER
FALL
3725.0
3724.0
3723.0
3722.0
3721.0
3720.0
3719.0
3718.0
3717.0
3716.0
3715.0
3714.0
-7613.0
-7611.0
-7609.0
-7607.0
-7605.0

Figure 7 a-d. Isopleth maps of the mean grain size in the 0-5 cm sediment layer for each season. The horizontal and vertical axis display the longitude and latitude, respectively, in degrees, minutes and tenths of a minute (*e.g.*, 3716.0 represents 37° 16.0")

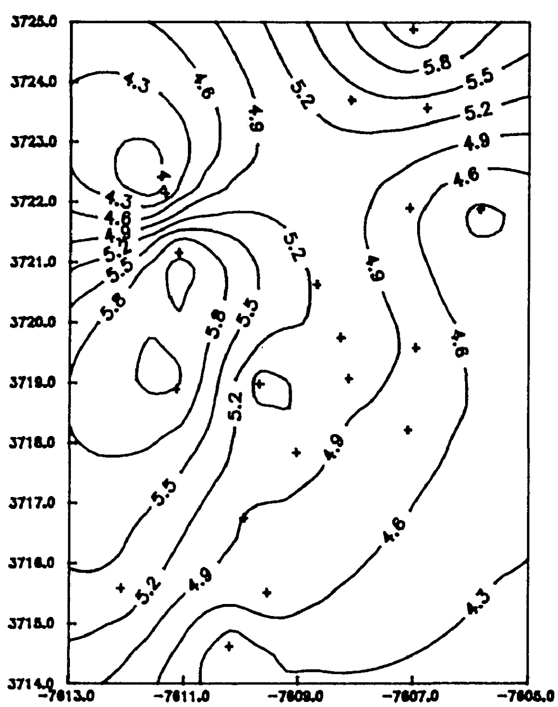
WINTER



SPRING



SUMMER



FALL

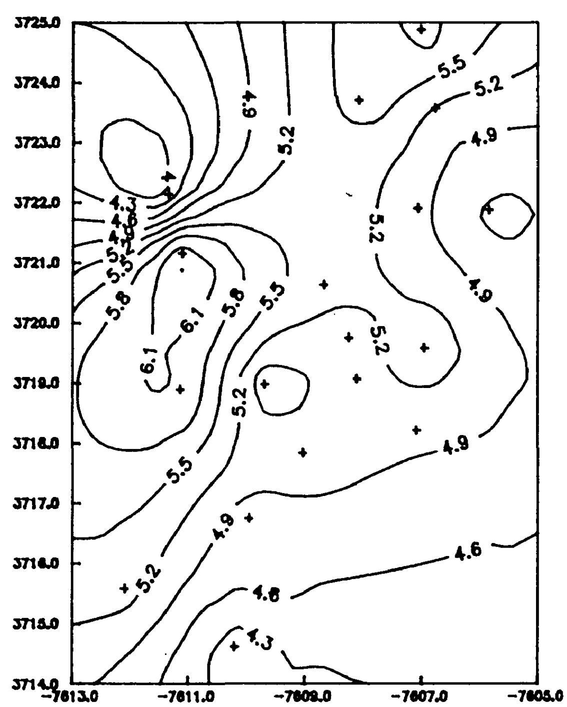


Figure 8 a-d. Isopleth maps for the silt to clay ratio in the 0-5 cm layer for each season. The horizontal and vertical axis display the longitude and latitude, respectively, in degrees, minutes and tenths of a minute (*e.g.*, 3716.0 represents 37° 16.0")

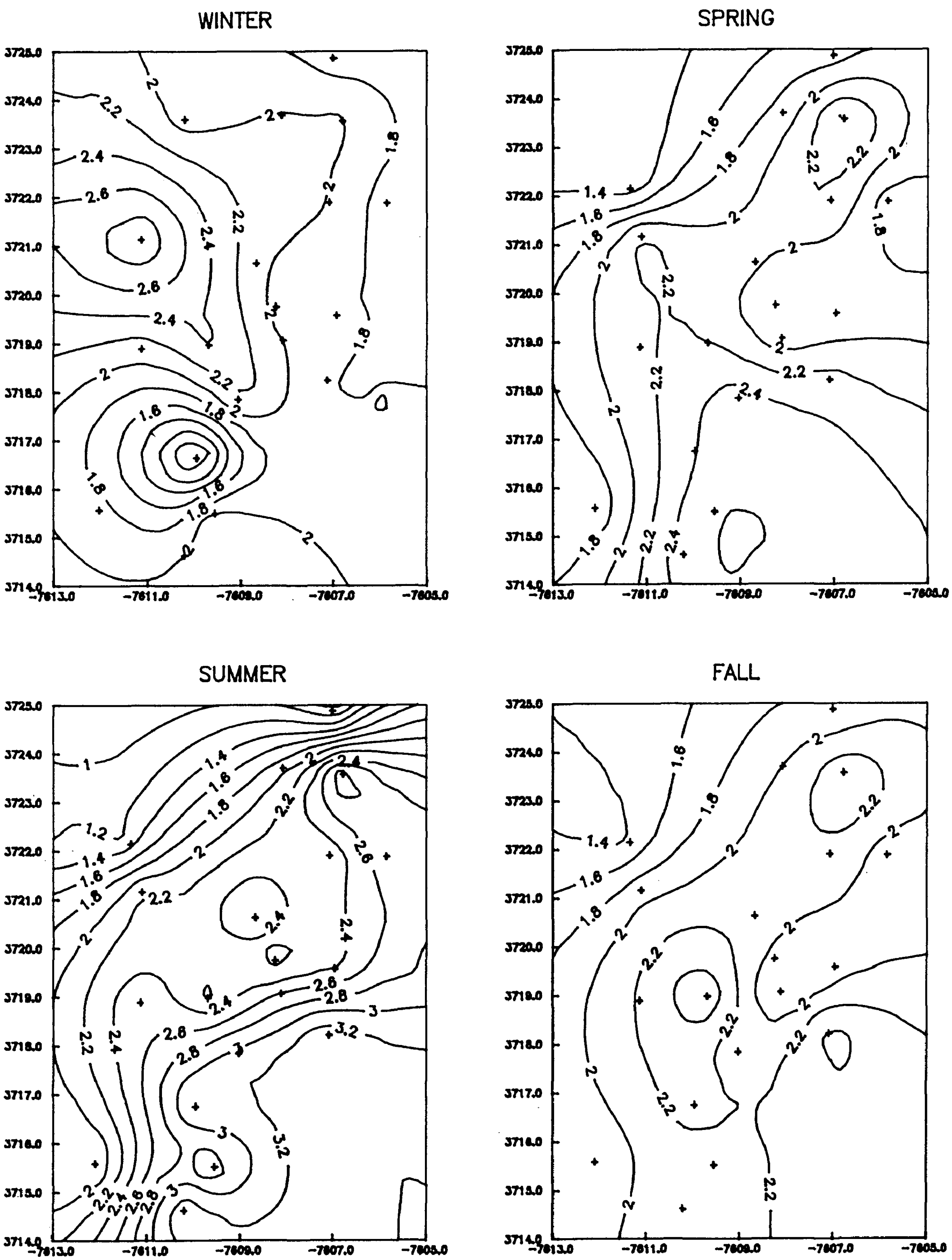
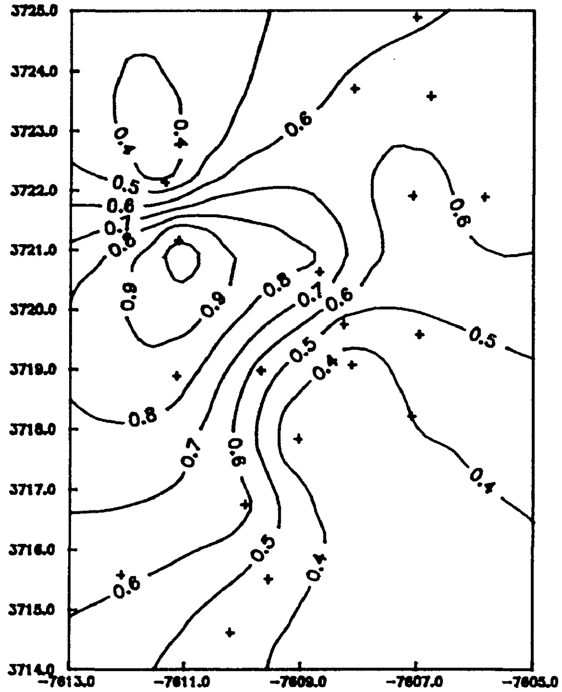
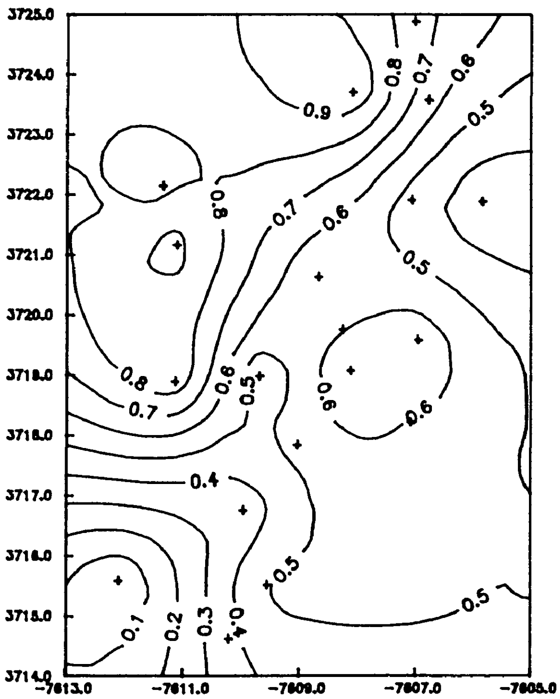

WINTER
SPRING
SUMMER
FALL
3725.0
3724.0
3723.0
3722.0
3721.0
3720.0
3719.0
3718.0
3717.0
3716.0
3715.0
3714.0
-7613.0
-7611.0
-7609.0
-7607.0
-7605.0

Figure 9 a-d. Isopleth maps for the organic carbon content in the 0-5 cm layer for each season. The horizontal and vertical axis display the longitude and latitude, respectively, in degrees, minutes and tenths of a minute (*e.g.*, 3716.0 represents 37° 16.0")

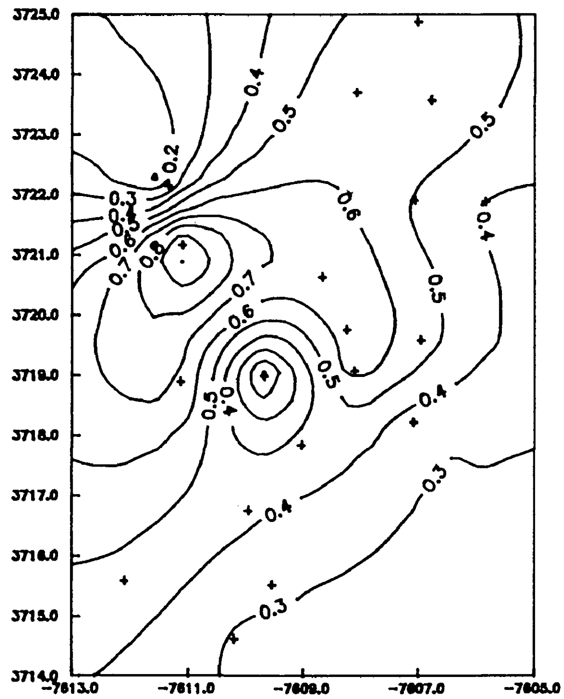
SPRING



SUMMER



FALL



different, showing an almost opposite trend, with increasing silt content to the southeast. The summer survey also has the greatest range of silt to clay ratio values compared to the other surveys.

The organic carbon isopleth maps (Figure 9) have no winter data due to lost samples - after collection in the field, samples were stored in a freezer to prevent further breakdown of organic material, during the winter cruise the freezer failed. The maps for spring, summer and fall do not display an obvious gradient, however, there is always higher organic carbon content on the western side of the area and lower values at the southern edge.

B) Two-way Analysis of Variance

The two-way analysis of variance for weight percent sand content, organic carbon content and mean grain size, show no significant differences between seasons or depth intervals (Tables 2a - 2c). The relocation of WTC02 has had no effect on this analysis for these three variables. Figures 10a - 10c are plots of the 95% confidence intervals for the variable means among seasons and depths. Although not statistically significant, it is interesting to note that the mean grain size is always largest in the 5-15 cm depth interval (4.0 - 5.0 phi is coarse silt, 5.0 - 6.0 is medium silt) and that the weight percent sand content is always greater.

Results for the silt to clay ratio show that there is a significant difference among seasons (Table 2d). Figure 10d reveals that the silt to clay ratio is significantly different between the winter and summer in the surface layer. The

Table 2a. Analysis of variance for percent sand content.

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig.level
MAIN EFFECTS	533.63132	4	133.40783	.686	.6030
by seasons	109.51809	3	36.50603	.188	.9047
by depth	424.11322	1	424.11322	2.180	.1420
2-FACTOR INTERACTIONS	60.572303	3	20.190768	.104	.9577
season by depth	60.572303	3	20.190768	.104	.9577
RESIDUAL	28020.113	144	194.58412		
TOTAL (CORR.)	28614.316	151			

Table 2b. Analysis of variance for organic carbon.

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig.level
MAIN EFFECTS	.2051586	4	.0512897	1.217	.3080
by season	.2051176	3	.0683725	1.622	.1885
by depth	.0000228	1	.0000228	.001	.9817
2-FACTOR INTERACTIONS	.0231884	3	.0077295	.183	.9075
eason by depth	.0231884	3	.0077295	.183	.9075
RESIDUAL	4.5098305	107	.0421479		
TOTAL (CORR.)	4.7381775	114			

Table 2c. Analysis of variance for mean phi size.

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	2.5049320	4	.6262330	1.338	.2586
by season	.7704572	3	.2568191	.549	.6497
by depth	1.7344748	1	1.7344748	3.707	.0562
2-FACTOR INTERACTIONS	.7919701	3	.2639900	.564	.6395
season by depth	.7919701	3	.2639900	.564	.6395
RESIDUAL	67.382527	144	.4679342		
TOTAL (CORR.)	70.679430	151			

Table 2d. Analysis of variance for silt to clay ratio.

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	3.0677763	4	.7669441	3.973	.0043
by season	2.9500599	3	.9833533	5.094	.0022
by depth	.1177164	1	.1177164	.610	.4445
2-FACTOR INTERACTIONS	.4960230	3	.1653410	.857	.4653
season by depth	.4960230	3	.1653410	.857	.4653
RESIDUAL	27.796495	144	.1930312		
TOTAL (CORR.)	31.360294	151			

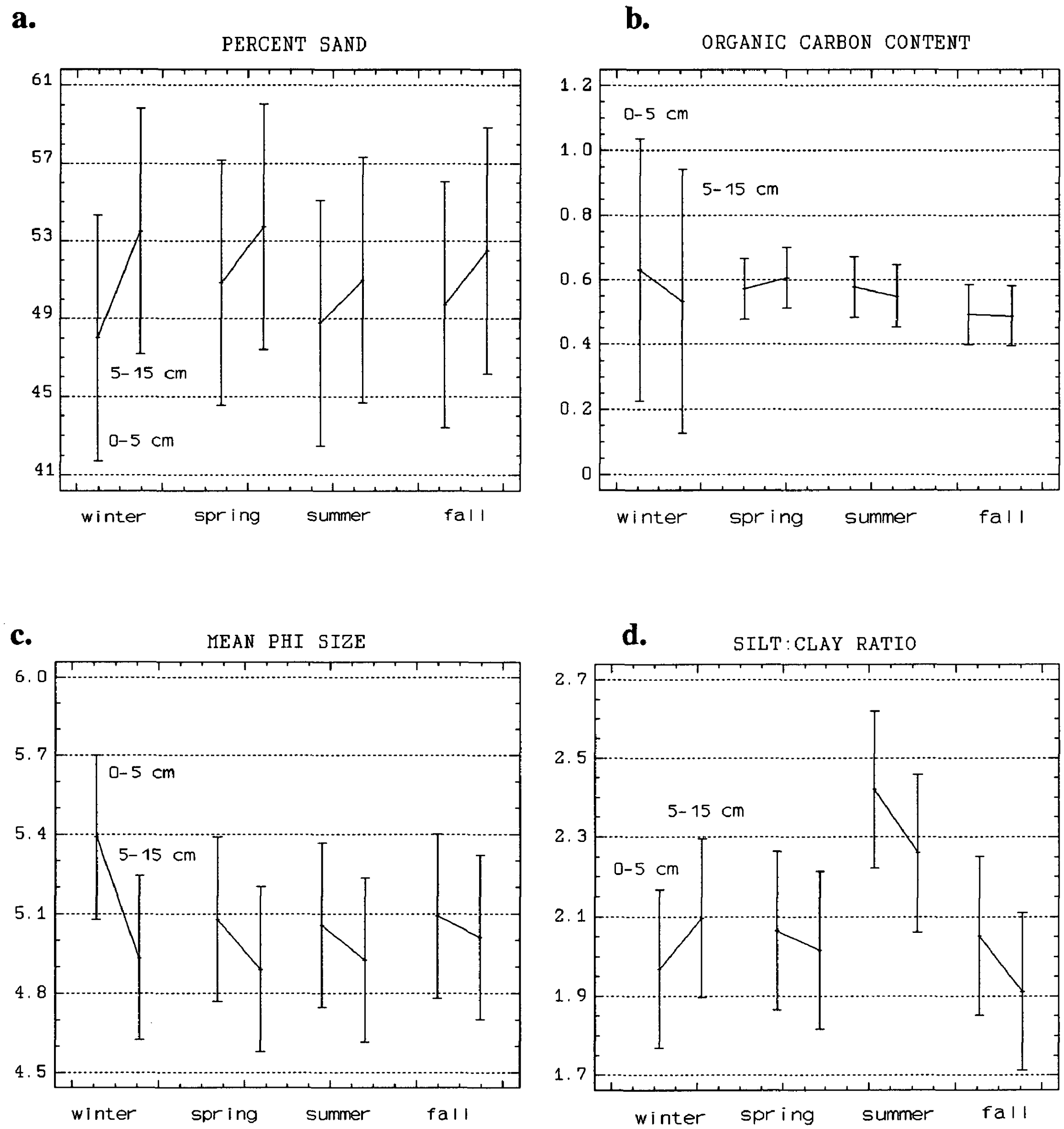


Figure 10 a-d. Ninety-five percent confidence intervals for the four variable means by season for each depth. Each set of interval bands represents the 0-5 and 5-15 cm depth intervals. The horizontal bars connect the means of the two sediment intervals; the vertical bars show the 95% confidence interval.

silt content is higher in the summer (mean ratio = 2.4) than in the winter (mean ratio = 1.9). The relocation of WTC02 may have influenced the difference between these two seasons. Another factor may be biological activity as this coincides with a significant increase in the boundary roughness, attributed to increased biological activity, recorded by sediment profile camera images during the same period (Diaz *et al.*, 1985).

C) Spatial Autocorrelation Analysis

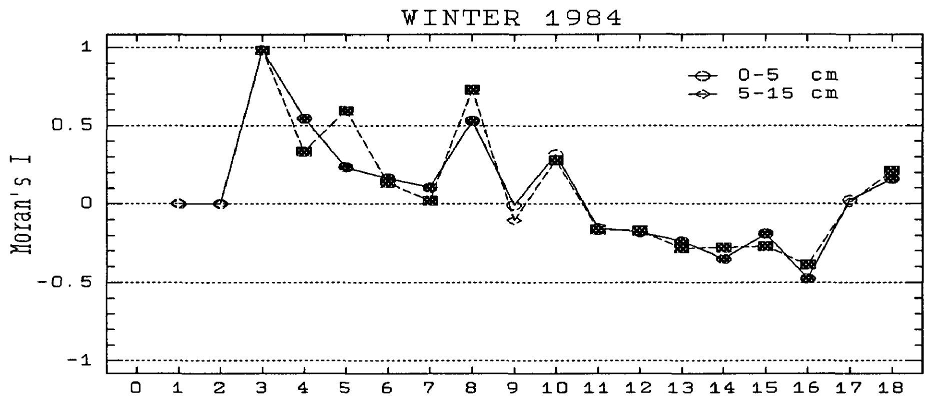
The correlograms (Figures 11 - 14) display the values of the autocorrelation coefficient, Moran's I, on the vertical axis and the distance class on the horizontal axis. The distance class is in meters, each tic representing the upper bound of the class. Significant autocorrelations (α = 0.05) are indicated by the darkened squares. Significance was tested under a two-tailed null hypothesis of no autocorrelation. A two-tailed test was selected as there is no reason to expect either only positive or only negative correlations.

The spatial correlograms (Figures 11a-d) for weight percent sand show virtually identical patterns for both the surface and subsurface sediment layers where autocorrelations are significant. The winter isopleth map for this variable exhibited a west to east gradient of increasing sand content. This is manifest in the correlogram (Figure 11a) as a significant positive correlation at the lower distance classes and significant negative correlations at the higher distance classes. This is a typical signature of a gradient (Sokal and Oden, 1978), wherein, localities closest together are similar and those far apart are disparate. The spring, summer and fall correlograms (Figures 11b-d) for percent sand content display a pattern unlike that for winter, but are generally similar to each other. These correlograms also have a significant negative peak in the 3000 meter distance class, not evident in the winter correlogram. This may be a result of the relocation of station WTC02 creating a small patch. The sharp dissimilarity over a short distance causes a negative correlation in this distance class. In all of the correlograms for percent sand content there is a significant and persistent peak of positive correlation at the 4000 meter distance class. This may be an artifact of the station interpoint distance. The approximate average distance between stations is 4000 meters, the interpretation of the correlogram is that most neighboring stations appear to be similar to each other.

Correlograms for the organic carbon content are shown in Figures 12a-c. No correlogram exists for the winter cruise due to loss of samples. Variations are seen in the resulting correlograms from season to season. The correlograms for spring and fall (Figures 12a and 12d) display similar patterns for both the 0-5 and 5-15 cm layers. The summer correlogram (Figure 12b) exhibits different correlograms for the surface and subsurface sediment layers. All the correlograms display oscillatory patterns, particularly at the lower distance classes. Sokal and Oden (1978) refer to this type pattern as "crazy quilt" and suggest that it is representative of a distance-dependant process. Organic carbon is closely associated with finer grained sediments, particularly clays. This is in part due to the greater surface area available for adsorption of organics, and to sediment permeability, *i.e.*, organic carbon would be more easily diluted in coarser grained,

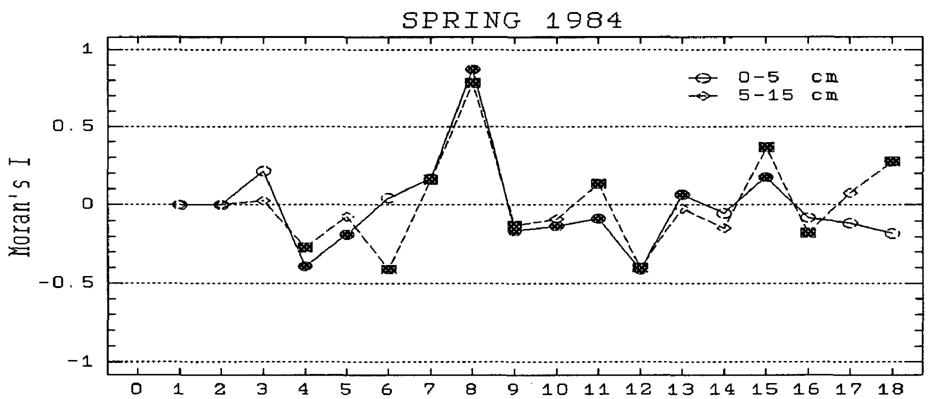
Figure 11 a-d. Spatial correlograms of percent weight sand for each season. Significant coefficients ($p < 0.05$) are indicated by filled point markers. Distance tics along the horizontal axis represent class increments of 500 meters.

a.



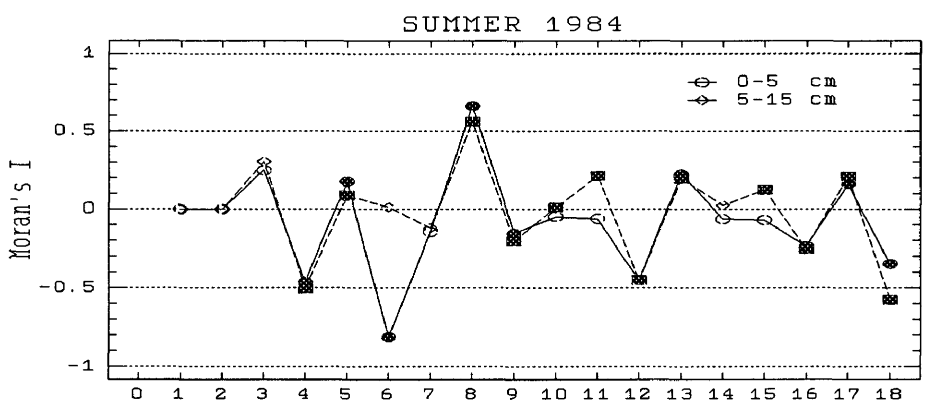
WINTER 1984
0-5 cm
5-15 cm
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

b.



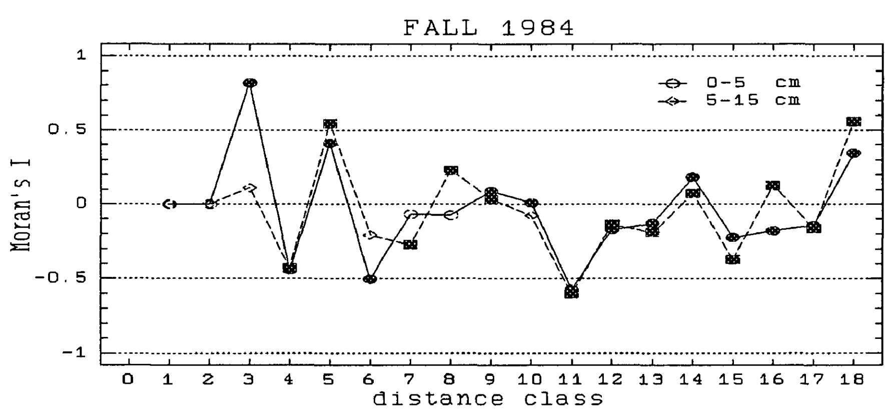
SPRING 1984
0-5 cm
5-15 cm
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

c.



SUMMER 1984
0-5 cm
5-15 cm
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

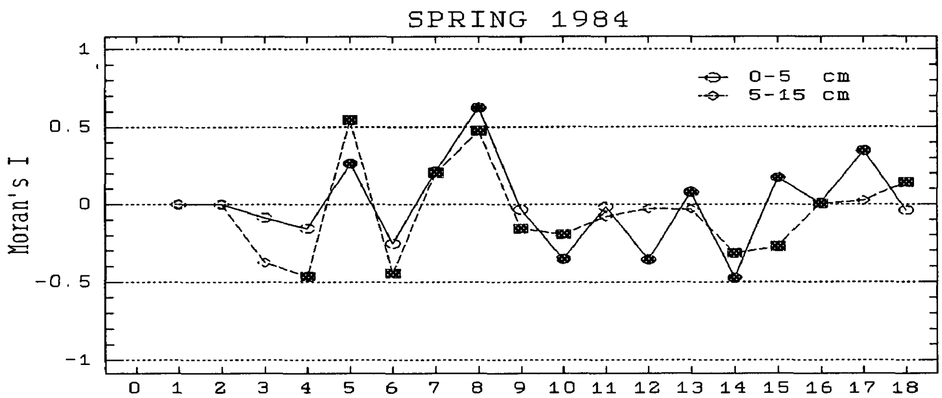
d.



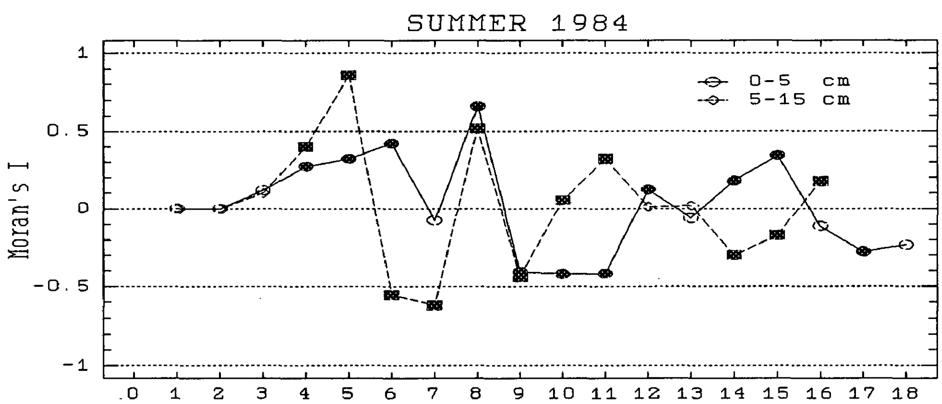
FALL 1984
0-5 cm
5-15 cm
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
distance class

Figure 12 a-c. Spatial correlograms of percent organic carbon content for each season. Significant coefficients ($p < 0.05$) are indicated by filled point markers. Distance tics along the horizontal axis represent class increments of 500 meters.

a.


SPRING 1984
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
0-5 cm
5-15 cm

b.


SUMMER 1984
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
0-5 cm
5-15 cm

c.

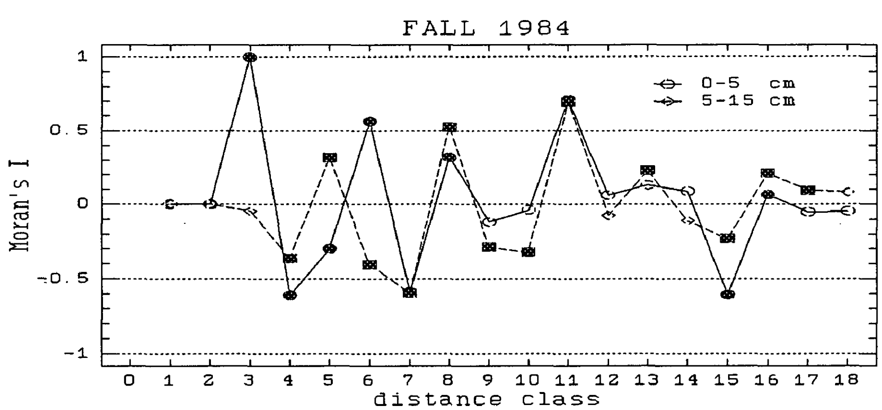
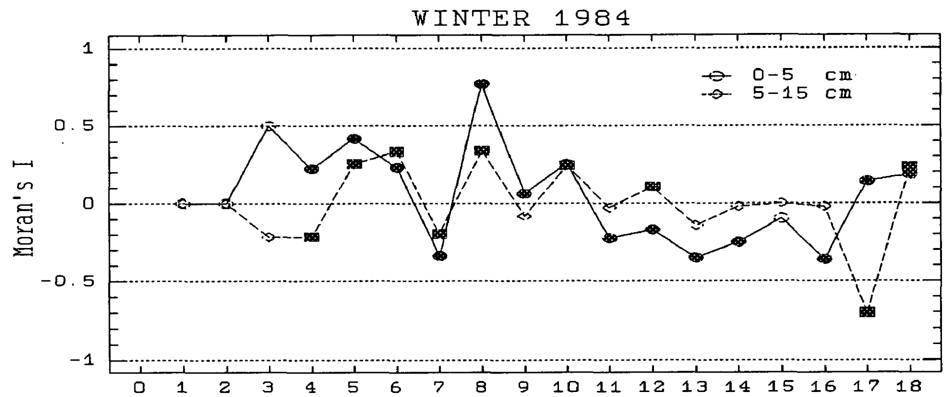

FALL 1984
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
distance class
0-5 cm
5-15 cm

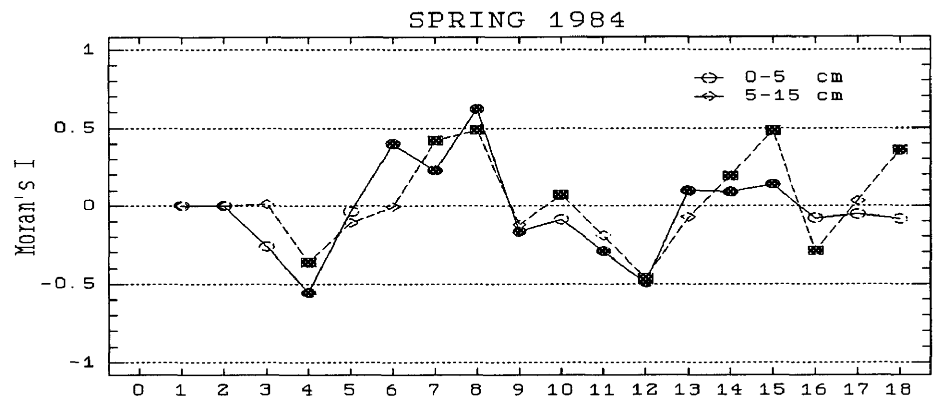
Figure 13 a-d. Spatial correlograms of mean grain size (phi units) for each season. Significant coefficients ($p < 0.05$) are indicated by filled point markers. Distance tics along the horizontal axis represent class increments of 500 meters.

a.



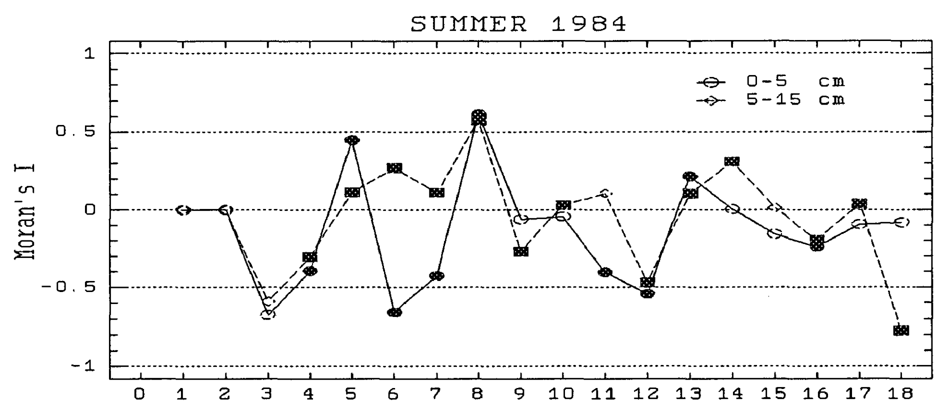
WINTER 1984
0-5 cm
5-15 cm
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

b.



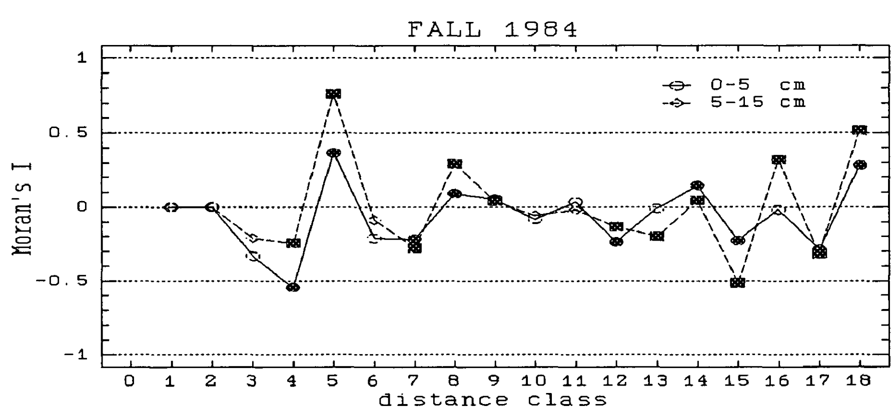
SPRING 1984
0-5 cm
5-15 cm
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

c.



SUMMER 1984
0-5 cm
5-15 cm
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

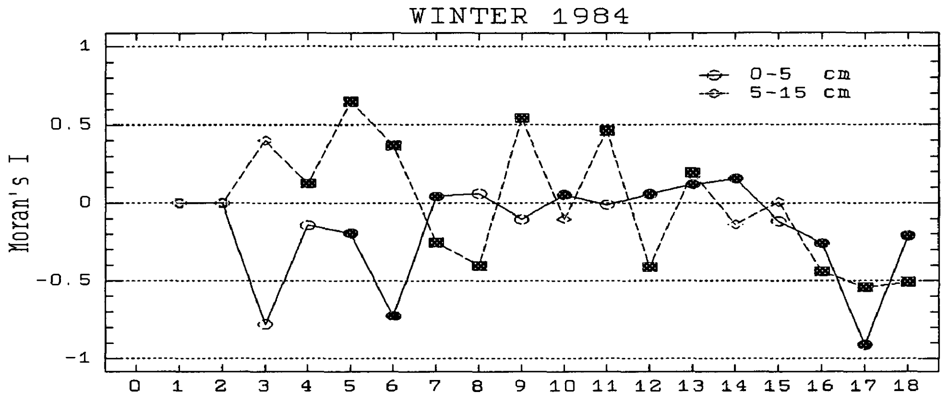
d.



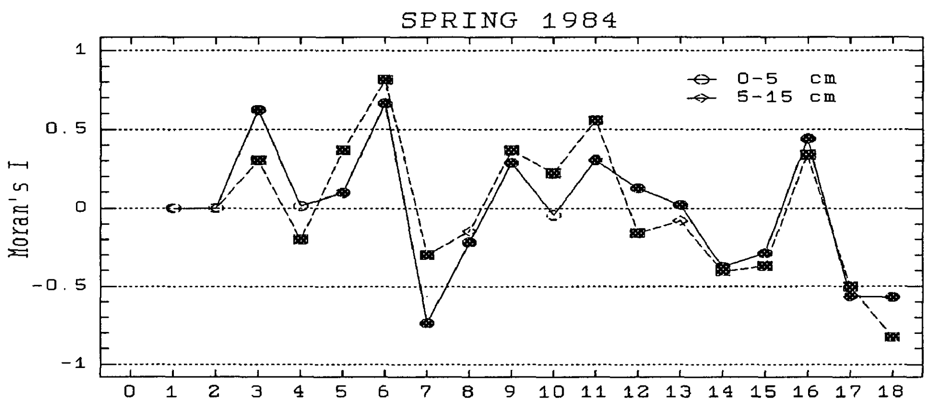
FALL 1984
0-5 cm
5-15 cm
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
distance class

Figure 14 a-d. Spatial correlograms of the silt to clay ratio for each season. Significant coefficients ($p < 0.05$) are indicated by filled point markers. Distance tics along the horizontal axis represent class increments of 500 meters.

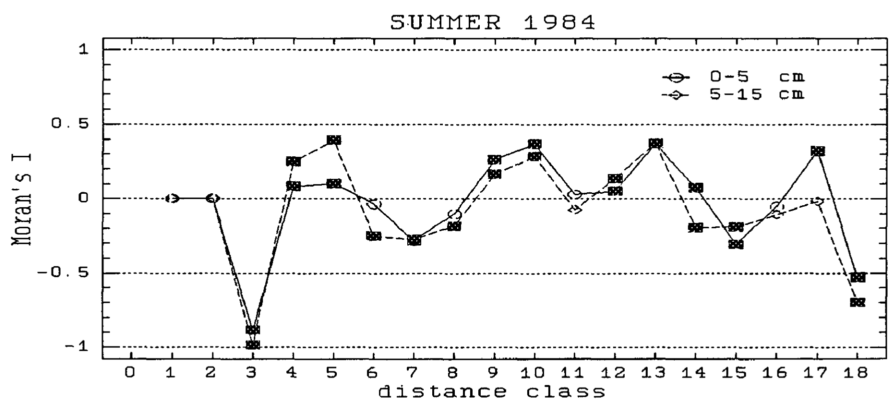
a.


WINTER 1984
0-5 cm
5-15 cm
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

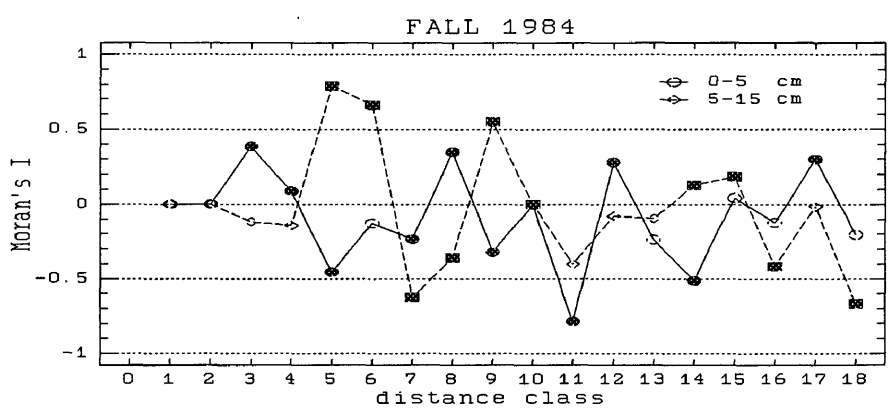
b.


SPRING 1984
0-5 cm
5-15 cm
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

c.


SUMMER 1984
0-5 cm
5-15 cm
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
distance class

d.


FALL 1984
0-5 cm
5-15 cm
Moran's I
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
distance class

permeable sediments (Biggs, 1967; Thomas, 1969; Folger, 1972). Because of this association with the fine grained sediments, it would be expected that the organic carbon may be carried with these particles as they are winnowed and transported by tidal currents. Thus, the correlograms display the oscillatory patterns typical of a distance-dependant process, *e.g.*, sorting. Throughout the three seasons and for both sediment layers, there is a persistent peak of positive spatial autocorrelation at 4000 meters. Again, this could reflect the station interpoint distance, this distance class will be comprised of station neighbors many of which may not be significantly different from each other.

The resulting correlograms (Figures 13a-d) for mean grain size display similar patterns for both sediment layers through all four seasons excluding the summer, in which there are significant negative correlations in the 3000-3500 meter classes. There is the peak of significant positive correlation at 4000 meters in all plots. This series of plots generally mimics the series resulting from the analysis of weight percent sand content. The winter correlogram shows some characteristics associated with the signature of a gradient in which there are increasing negative correlations as the distance class increases.

Figures 14a-d are the correlograms for the silt to clay ratio. The most obvious feature is the variation of the correlograms with time and depth. In the spring and summer, the resulting correlograms for the 0-5 and 5-15 sediment layers are nearly identical, however, the two layers in the winter and fall correlograms are almost completely out of phase. The winter correlogram does not display any of the characteristics associated with a gradient as seen in the results from the percent sand and mean grain size.

The preceding results demonstrate that spatial patterns do exist and are quantifiable by autocorrelation in correlograms. These patterns do not appear to vary for the percent sand content or mean grain size, when the winter sampling survey is excluded. Since station WTC02 was moved a considerable distance, resulting in appreciably different isopleth maps and correlograms, it is not seem appropriate to include the results from the winter survey when making comparisons. The silt to clay ratio correlogram did considerable variations in spatial patterns from season to season and with depth, even with the winter survey excluded. The organic carbon content also exhibits differences with time, but changes with depth are only apparent in the summer.

DISCUSSION

It was expected, that if the biota significantly affected sediments (*e.g.*, Diaz *et al.*, 1985) or that hydrodynamic forcings may be such that significant resuspension events may be occurring regularly throughout the year (*e.g.*, Boon *et al.*, 1987), there should be some distinction in the sediment character from one season to the next. The results of the two-way analysis of variance show no statistically significant seasonal differences except in the surface layer silt to clay ratios (S:C) between the summer (mean S:C = 2.4) and winter (mean S:C = 1.9). One possible explanation is the relocation of station WTC02 between the winter and summer seasons. However, the silt to clay ratio isopleth maps (Figure 8a-d) show that the WTC02 was moved into a region of lower S:C values. The winter mean S:C was lower than that for the summer, therefore, the difference between the two seasons does not seem related to the relocation of WTC02. Another explanation may be the increased biological activity during the summer months as evidenced by a significant increase in the boundary roughness, recorded by the sediment profile camera (Diaz *et al.*, 1985). The increased roughness was attributed to fecal mounds of maldanid polychaetes. Maldanid polychaetes are infaunal subsurface deposit feeders. Their "conveyor belt" processing pelletizes sediment, effectively increasing the *in situ* modal grain size of the sediments (Rhodes and Boyer, 1982).

Increased turbulence at the bed increasing sediment resuspendibility and winnowing of the finer fractions, may be another factor influencing the difference in S:C between the two seasons. Increased turbulence may be brought about by the presence of the maldanid fecal mounds themselves (*e.g.*, Nowell and Church 1979). Although the study by Boon *et al.* (1987) took place after this study's sampling, that finding of near bottom turbulence resulting from internal waves associated with spring-neap cycles and stratification suggests that such turbulence may have been, and continues to be, occurring at times of the year not associated with typical resuspension events (*e.g.*, hurricanes, winter storms).

The change in silt to clay ratios from winter to summer may also be the result of seasonal discharges from the western shore sub-estuaries and shore erosion. Byrne *et al.* (1982) proposed a sediment budget for the Virginia portion of the Bay with implications that the tributaries are sources rather than sinks of sediments. Diaz *et al.* (1985) also attributed the overall east to west cross-bay gradient of increasing mud content to these sub-estuaries. However, Schubel and Carter (1976) had previously concluded that only minor amounts of sediment were escaping from these sub-estuaries and that most riverine sediments were trapped in turbidity maximums at the head of the bay and tributaries. A study by Fedosh (1987), using satellite images of the southern Bay taken over a nine year period, found that spring data showed relatively low turbidity levels and that the highest values had actually occurred during the winter.

Three other factors may also be influencing the variability observed in the S:C ratios, but how these factors are manifest is not yet clear. First, the silt to clay ratio is the most sensitive to lab handling procedures. Processing of the sediment samples may mask the silt to clay ratio of natural sediments that have been pelletized and aggregated by organisms. Thus the silt to clay ratio data may not follow the trends of other parameters because it is not representative of actual conditions. Second, Wolf Trap has been documented as a preferred wintering site for the blue crab, *Callinectes sapidus*, a major fishery of the Chesapeake Bay (Schaffner and Diaz, 1988). The winter dredge fishery concentrates on Wolf Trap and other basin habitats in harvesting the crabs. The harvesting method involves the use of rakes with tines several inches long, capable of severely disturbing the bottom sediments (R.J. Byrne, pers. comm., 1989) Such disturbances could resuspend the sediments causing the winnowing of the finer fractions, or could simulate the effect of intense biological reworking.

A third factor is biological rain, *i.e.*, the flux of organic particulate matter to the bottom sediments. A preliminary report (Wetzel and Neilson, 1988) showed that hydrographic and water column particulate matter was highly variable, spatially and temporally, in the lower Chesapeake Bay. The report suggests that the magnitude of the particulate flux to the bottom may be linked to ambient water column particulate concentrations and the degree of stratification. Some of the difference in the S:C ratio between seasons may be associated with this biological rain if the fluxes are found to be significant.

Further insight as to which processes may be dominating at Wolf Trap and ultimately affecting the bottom mobility can be gained by examining the general patterns displayed by the correlograms. A signature of seasonal pulses of sediment, *i.e.*, the "spring freshets," would be a surface layer of silt and clay sized particles deposited in the spring. The ANOVA results do not show any significant differences during the spring between the surface and subsurface layers, or from the spring to any other season. However, the spring correlogram for the organic carbon content does show disparity between the 0-5 and 5-15 cm layer not seen in any of the other parameters. The surface (0-5 cm) correlogram displays the oscillatory behavior associated with a distance-dependant generating mechanism (Sokal and Oden, 1978) which could be a result of progressive mixing of organic matter during discharge events.

One of the most obvious features of the silt to clay ratio correlograms is the convergence of the surface and subsurface layers in the spring and summer. This is strong evidence for similar processes acting within both layers, such as would be expected from increased biological activity. The sediment profile images taken at the time (Diaz *et al.*, 1985) reveal well-developed biogenic structures to a depth of 12 cm and a maximum redox potential discontinuity (RPD) of 20 cm. The RPD represents the boundary between oxidized and reduced sediments and is an indicator of the degree of biologic activity. Schaffner *et al.* (1987) examined radiographs from the basin region and found that during the summer the sediments were highly reworked with no physical structures.

The dissimilarity in the silt-to-clay-ratio correlograms for the two layers during the winter and fall indicate different processes are present. Radiographs from the Wolf Trap region have shown that physical laminations were the dominant sediment structure in winter and early spring, reflecting minimal biotic activity due to depressed temperatures (Schaffner *et al.*, 1987). Thus, as biological activity decreases allowing physical processes (storm generated currents, tidal oscillations) to dominate, changes become apparent in the surface layer relative to the subsurface layer.

The absence of detectable differences in the other variables analyzed suggest that the silt to clay ratio is a more sensitive measure. Driscoll *et al.* (1985) state that while it is useful to know the exact percentages of silt and clay, the ratio of silt to clay yields greater information related to size fractionation during depositional processes. Because silt and clay form a cohesive mud, the critical erosion velocity is controlled by cohesiveness and not by grain size, therefore, when muds are eroded both silt and clay are suspended. The enhancement of one component over the other is dependent on preferential settling as current velocity increases or decreases (McCave and Swift, 1976). Ledbetter and Ellwood (1980) also preferred information contained in the finer fractions. They used a combination of the magnetic properties of sediments and the mean size of the silt fraction on the deep ocean floor as an indicator of current direction and magnitude.

CONCLUSIONS

Results from the ANOVA show no difference from season to season over the period of a year, or with depth for the four textural parameters examined, except for the silt to clay ratio. In terms of "conventional" textural parameters the region appears stable. However, a significantly enhanced silt content in the summer compared to the winter suggests that a number of processes could be acting within the region. Such processes include seasonal fluctuations in biological activity, increased turbulence near the bottom related to the physical regime or from the biogenic structures, seasonal pulses of sediment from western shore tributaries, or lab processing procedures. Correlograms from spatial autocorrelation analysis revealed the existence of spatial patterns, how these patterns varied with time and depth, and provided further insight as to the processes dominating the region. Interpretation of the correlograms support the dominance of biological activity in the summer. In combination with the previous work done at Wolf Trap, it appears that the bottom sediments are relatively mobile, i.e, the benthic regime is dynamic on at least a seasonal time scale. Implications are that while other bay-stem plain environments may also appear flat and featureless, or "boring," the bottom sediment dynamics potentially could be very dynamic.

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