SOUTHEASTERN GEOLOGY

PUBLISHED AT DUKE UNIVERSITY DURHAM, NORTH CAROLINA

VOL. 16 NO. 3 FEBRUARY, 1975

SOUTHEASTERN GEOLOGY

PUBLISHED QUARTERLY

AT

DUKE UNIVERSITY

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ENVIRONMENTAL ANALYSIS OF THE SANTEE RIVER ESTUARIES: THIRTY YEARS AFTER DIVERSION

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ABSTRACT

The hydrology and distribution of sediments in the North and South Santee River Estuaries have been analyzed to determine the effects of the 1942 diversion on the system.

Diversion decreased the freshwater inflow from 525 m^3/s to 14 m^3/s, changing the estuaries from a salt-wedge stratified type to a partially mixed type. A decrease in sediment supply also accompanied diversion. To adjust to this new regime the estuaries are filling in with sediment derived from the ocean. These sediments, generally finer than those associated with fluvial deposits have penetrated more than three kilometers inland and have decreased the depths in the areas close to the mouths.

Upon rediversion the system will revert to salt-wedge stratified estuaries. Rediversion will alter existing channel configuration especially in areas close to the mouths where the marine sands have been deposited.

INTRODUCTION

In 1942, completion of the Santee-Cooper Dam diverted most of the fresh water flowing in the Santee River into the Cooper River which empties into Charleston Harbor. After diversion the Santee River fresh water discharge decreased from 525 m^3/s to 14 m^3/s; suspended sediment discharge decreased from about 3×10^6 tons per year to approximately 1.3×10^4 tons per year. Reduction of both fresh water and suspended sediment discharge terminated either a state of dynamic equilibrium or active progradation of the Santee River Delta and resulted in an abandonment of a deltaic lobe.

Diversion altered both the Santee River and the Ashley-Cooper-Wando-Estuary. The effects of diversion on the Ashley-Cooper-Wando-Estuary have been well documented by Schubel (1971) and Schubel and Pritchard (1972). The diversion, with attendant increase in flow, changed the estuary from a well-mixed to a salt-wedge stratified estuary. A major increase in shoaling occurred. The mouth of the estuary is Charleston Harbor and the increased shoaling required 29 times more dredging than in pre-diversion time and increased annual dredging costs more than 33 times. The U. S. Army Corps of Engineers (App. A, 1966) defined the source of the material causing shoaling as follows: 40 percent originates from the Congaree Wateree watershed (passing through the Santee-Cooper Dam), 33 percent is eroded from the bed and banks of the upper Cooper River as a result of the increased flow in the channel, and 27 percent is from sources operative before diversion. The need to dredge the harbor has created very serious problems because of the limited area for spoil disposal. The solution to this problem appears to be elimination of the primary sources of sedimentation and the reduction of inflow into the harbor. To achieve this goal, the U. S. Army Corps of Engineers has proposed a rediversion of 80 percent of the flow of the Cooper River back into the old Santee River channel.

The effects of channelization and diversion of natural water systems has recently been the subject of considerable debate. Environmental impact studies made on systems that have been changed show that man's past effects on estuaries have been poorly and incompletely planned, unimaginative and frequently destructive (Cronin, 1967). Lately, man has realized his past mistakes and has tried to take corrective measures to return environmental systems to their natural status. The diversion and proposed rediversion of the Santee River is such a case.

This study was made to determine the effects of the original diversion on the Santee River system, to establish the present hydrological and sedimentological conditions, and develop a hypothesis to describe the effects of rediversion on the system. To accomplish these objectives, a sedimentary framework will be established from a study of the surficial bottom sediments. A sedimentary environmental model of existing conditions will then be developed using data of an earlier study (Cummings, 1970) and from additional data collected by the authors. These models will be used to predict the effect of the proposed rediversion on the system.

Acknowledgments

This research was supported through Sea Grant #NG-33-72, The College of Charleston Foundation and a Sigma Xi Grant-in-Aid.

The authors would like to express our appreciation to Robert Ehrlich, the University of South Carolina, for his stimulating discussions and assistance in the preparation of the manuscript.

AREA OF STUDY

The Santee River System is located approximately 75 kilometers northeast of Charleston, South Carolina, and 30 kilometers southwest of Georgetown, South Carolina (Figure 1). Located at the southern edge of Long Bay, north of Cape Romain, the Santee River Delta is an area of sediment accumulation and progradation onto the Atlantic continental shelf. Extensive deltaic plain deposits are separated by two distributaries, the North and South Santee Rivers, and a bay, the North Santee Bay. Twenty-three kilometers from the ocean the Santee River bifurcates to form the North and South Santee distributaries.

In 1942, construction of the Santee-Cooper Dam decreased fresh water inflow to 14 m^3/s. Under the license granted by the Federal Power Commission a minimum flow of 14 m^3/s must be released from Lake Marion to the Santee River. The amount of fresh water flowing into the South Santee is limited to approximately 2 m^3/s, or 15 percent of the total water inflow, by a constriction of the South Santee below the distributary bifurcation.

METHODS

A series of transects one kilometer apart was established normal to the axis of the estuary. A regular interval was chosen from transect locations because a preliminary study of salinity by the authors revealed that a linear relationship existed between salinity and distance from ocean. Two-hundred and fifty stations were sampled during the summer of 1972. In the South Santee each transect was assigned a letter; cardinal numbers were used to denote position within the transect. In the North Santee each transect was assigned a cardinal number; letters were used to denote position within the transect. In both rivers each transect series began on the north or east bank. Locations of transects and stations are shown in Figure 1.

Seven liters of bottom sediment were collected at each station from multiple samples with a 1/10 m^2 Peterson grab sampler. A seven-hundred and forty milliliter aliquot of each sample was removed from the top centimeter of the first grab taken and retained and the remainder of each sample was washed through a one-millimeter sieve to collect molluscan shells and fragments. The aliquot was analyzed for carbonate content, relative proportion of sand, silt-clay fraction, and median diameter in that order. Standard wet sieving methods were used to determine sand percent. The sand fraction of the sample, after

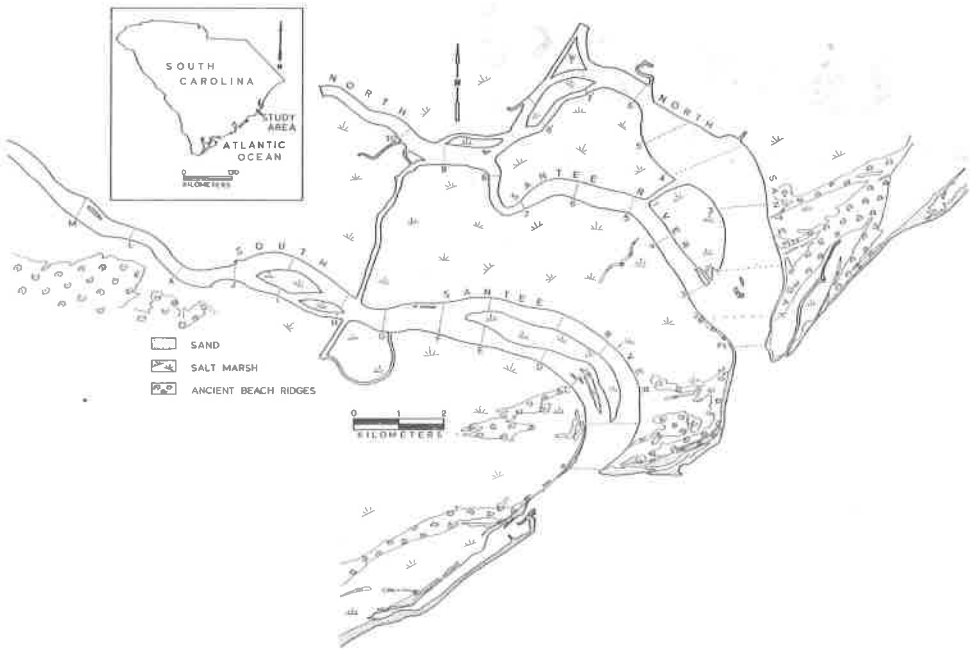

Figure 1. Location of study area and sampling locations: South Santee transects (A-M); North Santee transects (Pt-10); North Santee transects (2'-8').

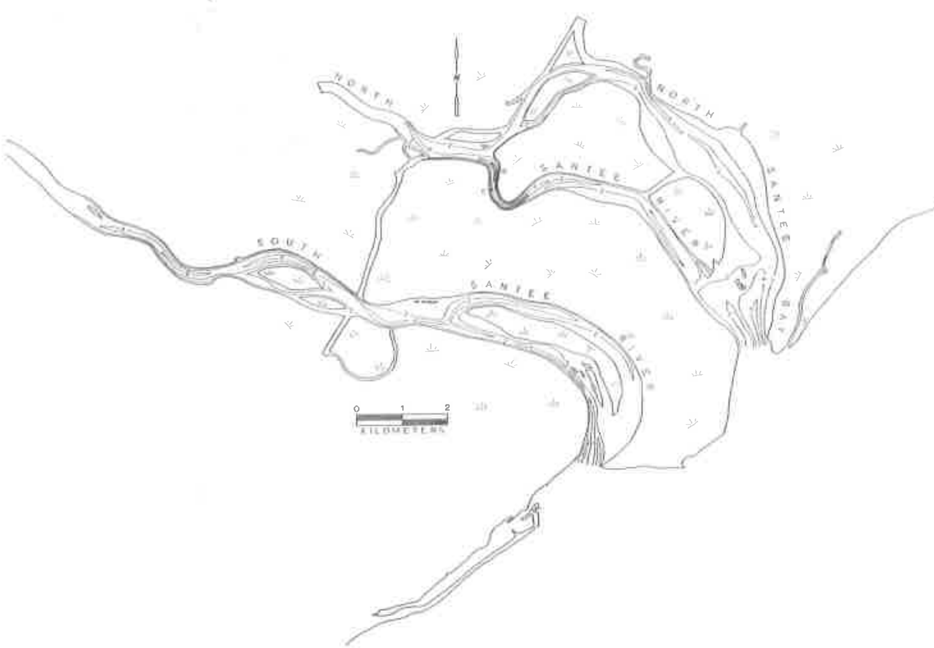

Figure 2. Bathymetric map at mean low water (2 meter intervals).

treatment with HCL, was analyzed using a rapid sediment analyzer and the resulting cumulative frequency curve was used to obtain median diameter of the total sample.

Water depth, bottom water salinity, and bottom water temperature were recorded at each sampling station at the time of sampling. Additional salinity and temperature data were obtained at each transect during ebb and flood slack during the period of May-October, 1972. Salinity and temperature measurements were made with a Beckman RS-5 salinometer. Salinity measurements were also taken across transects during ebb and flood slack to determine whether horizontal gradients were present. Salinity and temperature measurements were also available from an earlier study on the Santee by Cummings (1970).

PHYSICAL ENVIRONMENT

Hydrology

Tide: Mean high tide in the Santee system is 1.34 meters above mean low water. The highest tide measured was 1.9 meters above mean low water while the lowest tide measured was 0.38 meters above mean low water (Cummings, 1970). Tidal discharge measurements made in the North and South Santee distributaries at approximately the same distances from the ocean (9 kilometers) indicate that the flow is greater in the North Santee. Nine kilometers from the ocean tidal flow in the North Santee was 555 m^3/s during both ebb and flood stages; in the South Santee the tidal flow was 435 m^3/s and 470 m^3/s at flood and ebb tidal stages, respectively (Cummings, 1970).

Bathymetry: The average depth of the Santee River system (Figure 2) is approximately three meters below mean low water. The greatest depth, nine meters, was recorded in the North Santee at Transect 8. Generally, the average depth of the North Santee is greater than that of the South Santee or the North Santee Bay. The North Santee Bay, which averages close to one-and-one-half-two meters in depth and never exceeds four meters in depth, is the shallowest system.

Freshwater inflow: The minimum fresh water inflow into the Santee River is maintained at 14 m^3/s. However, during times of flooding (ex., October 21, 1965), releases from the dam as great as 2430 m^3/s have been recorded (Cummings, 1970). Average fresh water inflow for the past three years (Table 1) indicates that the greatest releases occur during late winter and early spring and coincides with greatest rainfall. (U. S. Weather Bureau, Charleston, South Carolina, unpublished).

Salinity: Salinity decreases away from the ocean. The bottom water salinity of the estuary ranges from 35°/00 at the mouth to 6°/00 at the head at flood slack and 32°/00 at the mouth to 0°/00 at the head at ebb slack (Table 2). In general, the salinities of the South Santee are

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1970	14	15	222	48	14	14	14	14	14	14	14	14
1971	14	48	264	14	14	14	14	14	14	14	14	14
1972	87	63	14	14	15	29	14	14	14	14	14	14
1	87	63	14	14	14	14	14	14	14	14	14	14
2	87	63	14	14	14	14	14	14	14	14	14	14
3	87	63	14	14	14	14	14	14	14	14	14	14
4	87	63	14	14	14	14	14	14	14	14	14	14
5	87	16	14	14	14	14	14	14	14	14	14	14
6	87	18	14	14	14	14	14	14	14	14	14	14
7	87	106	14	14	14	14	14	14	14	14	14	14
8	87	280	13	14	14	11	14	14	14	14	14	14
9	87	371	14	14	14	14	14	14	14	14	14	14
10	87	216	14	14	14	14	14	14	14	14	14	14
11	87	91	14	14	14	14	14	14	14	14	14	14
12	87	91	14	14	14	14	14	14	14	14	14	14
13	87	116	14	14	14	14	14	14	14	14	14	14
14	14	164	14	14	14	14	14	14	14	14	14	14
15	17	87	14	14	14	14	14	14	14	14	14	14
16	223	18	14	14	17	14	14	14	14	14	14	14
17	357	16	14	14	16	14	14	14	14	14	14	14
18	363	14	14	14	14	14	14	14	14	14	14	14
19	368	14	14	14	14	14	14	14	14	14	14	14
20	374	14	14	14	14	14	14	14	14	14	14	14
21	374	14	14	14	14	14	14	14	14	14	14	14
22	350	14	14	14	14	14	14	14	14	14	14	17
23	194	14	14	14	14	14	14	14	14	14	14	58
24	91	14	14	14	14	17	14	14	14	14	14	88
25	70	14	14	14	14	108	14	14	14	14	14	88
26	18	14	14	14	14	156	14	14	14	14	14	88
27	16	14	14	14	14	124	14	14	14	14	14	298
28	14	14	14	14	14	88	14	14	14	14	14	253
29	14		14	14	17	43	14	14	14	14	14	141
30	14		14	14	16	14	14	14	14	14	14	66
31	14		14		14		14	14		14		14

Table 1. Average release rates into Santee River at the spillway near Wilsons Landing in cubic meters per second (data provided by S. C. Public Works Authority).

SALINITY ($^{o}/oo$)

	SOUTH SANTEE RIVER													NORTH SANTEE RIVER										NORTH SANTEE BAY							
DATE	A	B	C	D	E	F	G	H	I	J	K	L	M	Pt	2	3	4	5	6	7	8	9	10	2'	3'	4'	5'	6'	7'	8'	
5/21/72	26	26	24	21	20	20	17	14	10	9	8	4	2	20	19	17	15	14	11	10	8	6	5	19	19	17	14	13	10	8	(LOW SLACK)
	34	35	34	32	30	28	24	22	21	20	17	16	14	35	33	33	31	29	26	24	21	19	16	34	33	32	30	30	25	21	(HIGH SLACK)
6/17/72	24	22	22	22	19	18	18	15	14	11	8	5	3	26	24	23	23	19	17	13	11	8	6	23	20	18	16	17	14	10	
	35	33	33	31	30	27	26	24	20	18	15	13	13	27	24	22	18	15	12	11	10	8	8	24	25	22	21	19	15	10	
7/23/72	19	16	16	13	12	9	8	8	6	5	3	0	0	18	15	11	10	8	7	7	5	3	0	17	15	11	9	7	6	5	
	33	33	32	30	28	27	24	25	20	16	14	14	14	28	25	22	19	16	15	12	10	8	7	23	21	19	19	18	14	10	
7/9/72	28	26	26	23	19	19	16	15	13	10	9	6	4	27	24	21	20	18	15	12	10	9	6	22	22	21	19	18	14	11	
	32	31	30	31	29	28	24	23	22	21	17	13	13	29	27	24	20	17	15	14	10	10	8	25	22	20	19	20	14	12	
9/9/72	30	25	24	23	21	19	17	16	12	11	7	5	4																		
	34	34	33	31	29	28	26	24	19	17	15	14	13																		
9/30/72	32	30	30	30	23	22	22	17	13	12	10	6	5	28	25	23	21	19	16	14	12	10	7	24	23	22	20	20	16	12	
	35	34	34	32	31	31	29	28	24	21	19	17	15	32	30	28	27	26	23	22	19	17	15	29	29	29	27	28	23	19	
10/1/72	17	15	14	14	11	9	9	7	5	4	0	0	0	15	15	14	12	11	9	8	6	3	3	15	14	14	13	14	10	5	
	31	31	29	28	27	25	25	24	19	16	14	13	12	30	26	25	23	20	17	14	13	11	10	26	25	23	21	20	17	13	

Table 2. Lowest and highest salinities at ebb and flood slack, respectively, at each transect.

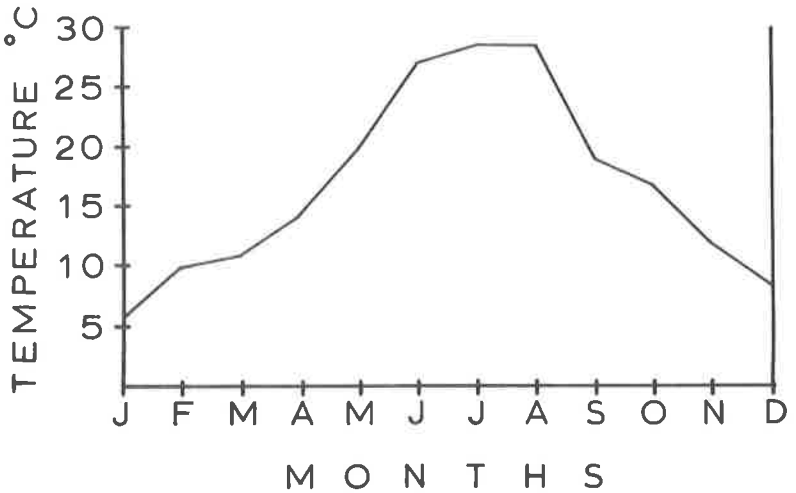

Figure 3. Average bottom temperatures for years 1968-1969 (data from Cunnings (1970).

higher than those of the North Santee, i. e., marine conditions penetrate farther inland in the South Santee than in the North Santee. Higher salinities are also observed in North Santee Bay and the northern or eastern sides of the estuary.

The estuary of the Santee River Delta can be classified as a partially mixed estuary under normal flow conditions (14 m/s), (Partheniades, 1972). However, during abnormal conditions the fresh water inflow is much greater and stratification occurs (Cummings, 1970).

Temperature: No diurnal bottom temperature variations greater than 2° Celsius were observed between any stations in the Santee River system but seasonal variations are quite prominent (Figure 3). Minimum temperatures are in January (6° C) and maximum in July and August (28° C).

Currents: The data are derived from measurements made by Cummings (1970). Velocities of 45.72 cm/s occur on the flood tide; velocities of 54.86 cm/s were recorded on the ebb tide. On occasion, velocities of 113.4 cm/s were recorded. However, large velocities occurred only during ebb tide and near the south and west banks. Maximum velocities during flood and ebb tides occur 0.3 to 1.5 meters below the surface (data from Cummings, 1970).

Dissolved Oxygen: Dissolved oxygen measurements were taken in December, 1968, and January, February, March, and June, 1969, by Cummings (1970). Seasonal stratification and variation of dissolved oxygen have been observed; dissolved oxygen concentration is higher near the bottom during the winter months and lower near the bottom during the summer months. The minimum dissolved oxygen concentration during the investigation was 5.9 mg/1 in the South Santee River during June; the maximum concentration was 16.0 mg/1 in the South Santee in January.

Sediment

The results of the surficial sediment studies show that in the Santee River system the substrate is predominantly coarse to fine sand, with minor amounts of silt and clay (Figure 4). The sand proportion is greatest at the mouths of the two distributaries and in their southern or western parts. Toward the heads of both distributaries, particularly near islands or meanders, sand content decreases. In the North Santee Bay and in the northern or eastern portion of the South Santee the sand proportion decreases. Approximately half of the area of the North Santee Bay is covered by sediments containing less than 70 percent sand.

Median diameters between 0 phi and 2 phi (coarse to medium sand) characterize the South Santee and North Santee proper. Median diameters finer than 2 phi (fine to very fine sand) are common only near islands and at the upper extremities of the system (Figure 5).

The lower reaches of the North Santee Bay and the northern side of the South Santee are dominated by sands having a median diameter finer than 2 phi. Areas having a median diameter of 3 phi or finer occur in the mid-reaches of the North Santee Bay, near island or delta plain banks and in areas of deep scouring (mouth of the South Santee and at Transect 8).

The data of two investigations (Lee, 1973; Mullins, 1973) in the North Santee and North Santee Bay, using different sampling methods and techniques, corroborate the sedimentary patterns defined in this study. Especially striking is the correspondence of the median diameter maps of the North Santee Bay.

Environmental Relationships

Hydrology: Present hydrological conditions are a result of the complex interaction of variables such as volume of freshwater run-off, bathymetry, the Coriolis effect, tidal flow, and wind direction. These variables interact to produce a complicated and diverse series of environmental conditions. The most noticeable effect of these variables is on the salinity in estuaries which has been well documented (Lauff, 1967; Tenore, 1972).

Sedimentology: Percent sand and median diameter show a close correlation with bathymetry. In general, higher sand content and larger median diameter are associated with channels. Median diameter also appears to be correlated with the direction of flood- or ebb-current flow. Large median diameter are associated with ebb current.

Ebb currents dominate the main channels of the North and South Santee distributaries. A comparison of Figure 2 with Figures 4 and 5 reveals that the extension of bottom channels is in the same direction as the extension of the large median diameters (0-2 phi) and high percent sand (greater than 90 percent). These sands are thought to be fluvially derived, that is, all three (bottom channels, high percent sand,

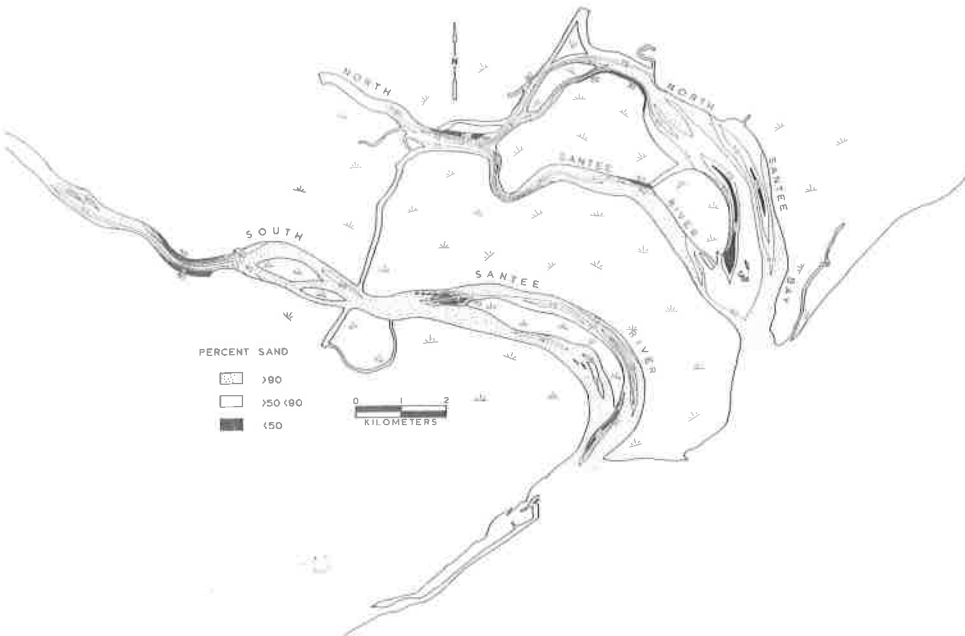

Figure 4. Distribution of sand fractions.

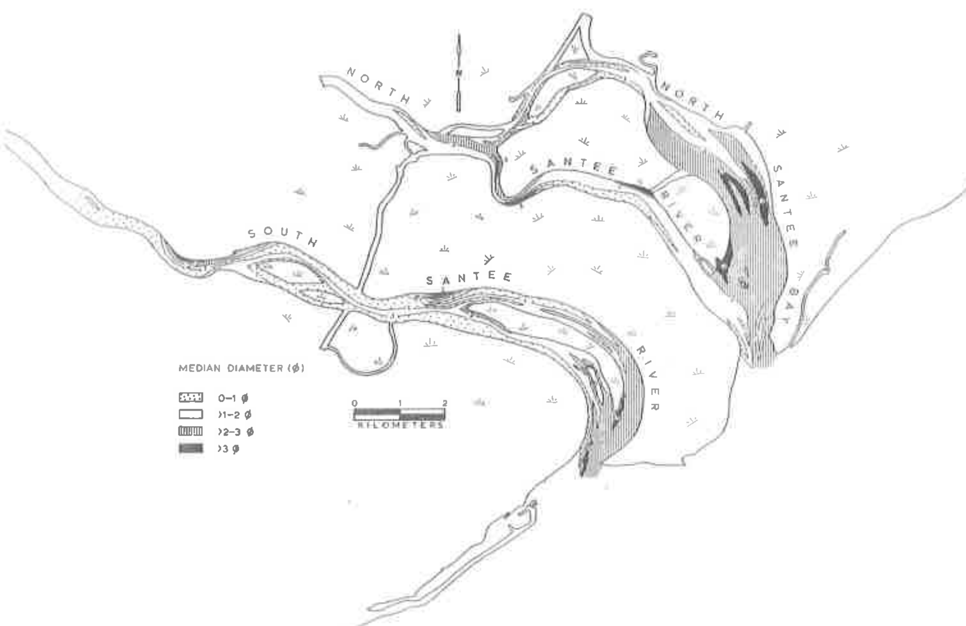

Figure 5. Distribution of median diameters.

and large median diameters) extend in a downstream direction. However, sediments with a low median diameter (2.5-4 phi) and with a low percent sand (less than 70 percent) extend in an upstream direction and appear to interfinger with those coarser sediments formed by the ebb current. Sediments with lower median diameters and less sand are found on the northern and eastern sides of the distributaries (Figure 5) and decrease in thickness from approximately 2.5m at the mouth to less than 0.17m in the North Santee Bay (Mullins, 1973). They are thought to be marine derived. An excellent example of this interfingering of ebb and flood deposits is seen in the North Santee Bay between Transect 2' and 4' (Figure 5). The coarser fluvial sediments extend landward on the flanks of the channels and on shallow subtidal banks.

A comparison of channel depths and configurations of the Santee system before and after diversion shows that infilling of the lower reaches of the main river channels has occurred (Mullins, 1973).

DISCUSSION

At the beginning of the last glacial stage, as sea level lowered, the gradient of the Santee River was increased and the Santee River prograded onto what is now the Atlantic continental shelf (Meade, 1969). Evidence from recent cores taken on the delta plain (Aburawi, 1972), indicates that the old Pleistocene channel was probably located further south at Cape Romain. As the sea retreated the Santee River Delta prograded farther seaward until deltaic ridges of sediment were deposited perpendicular to the coastline (Meade, 1969). As the ice began to melt sedimentation could not keep pace with sea level rise and the deltaic lobe was transgressed. Stabilization of sea level (3000 years before present), an average fresh water discharge of 525 m^3/s, and an average suspended sediment discharge of 3×10^6 tons per year permitted the Santee River Delta to recommence progradation.

From the time of stabilization of sea level until diversion, the mouth of the Santee River system was a salt-wedge estuary. The shallow depth of the Santee, its fresh water discharge, and low tidal range restricted penetration of the salt wedge and resultant net landward transport of sediment upstream into the system to within two to three kilometers from the present coastline (Aburawi, 1972). This indicates that the system greater than 2-3 kilometers inland from the ocean was dominated entirely by fluvial processes.

The building of the Santee-Cooper Dam in 1942 decreased the fresh water inflow from 540 m^3/s to 14 m^3/s and reduced the suspended sediment discharge. Reduction of fresh water inflow allowed salt water intrusion further inland and changed the Santee from a salt-wedge stratified estuary to a partially mixed estuary. This increased penetration of salt water resulted in the flocculation (Postma, 1967) of clay-sized material farther inland and caused a general shallowing of the entire system ; it also increased the silt-clay proportion inland thus decreasing median diameters.

A result of a greater relative tidal influence and the Coriolis Force is the landward extension of marine sands on the north and east sides of both rivers and the dominance of these sands in the North Santee Bay. Similar conditions have been noted by Neiheisel (1973) in the Delaware River estuary. These sands become thinner as they extend away from the mouths and interfinger with fluvial sands which extend seaward. The presence of these sands in the proximal areas of the mouth has drastically reduced the cross-sectional area of the channel and plugged the mouth (Mullins, 1973).

The estuaries and lower delta plain of the Santee River system are now an abandoned deltaic lobe undergoing seaward destruction and modification. Large trees and tree stumps and <u>in situ</u> deal <u>Modiolus demissus</u> (intertidal mussel), representing former back-barrier environments, now occur seaward of the sandy beaches, indicating a substantial retreat of land. Sedimentation is obviously not able to maintain the delta lobe. A comparison of two maps, 1934/35 and 1963, shows the amount of progradation before diversion and the extent of marine destruction since diversion (Figure 6).

The decrease in fresh water run-off and sediment discharge has resulted in the establishment of a complex system which appears to be in a transition stage between a delta and an estuary.

REDIVERSION

Prior to 1942, the velocity of flow, sediment discharge, and cross-sectional area of the Santee River can be assumed to have been in a state of equilibrium. According to Bates (1953), a decrease in velocity, theoretically, should increase the sediment accumulation rate (especially the larger particles) and decrease the cross-sectional area of the river; eventually, hydrodynamic equilibrium should be re-established. However, in the case of the Santee River, the sediment discharge was drastically reduced by the dam and equilibrium could not be achieved by accumulation of the fluvial sediments. Reduction of the channels' cross-sectional area by deposition of material coming down river is therefore minimal. Equilibrium is being achieved, to some extent, by the transportation of sand from the marine environment into the estuary.

The major questions to be answered concerning the channels' ability to contain the proposed rediversion are (1) to what degree has the system changed since diversion, and (2) how will rediversion affect present channel depth and configuration. It appears, however, that these questions can be answered using this idea of "system equilibrium". The present system is attaining equilibrium from oceanic-derived sediment, but this occurs only near the mouths of the channels.

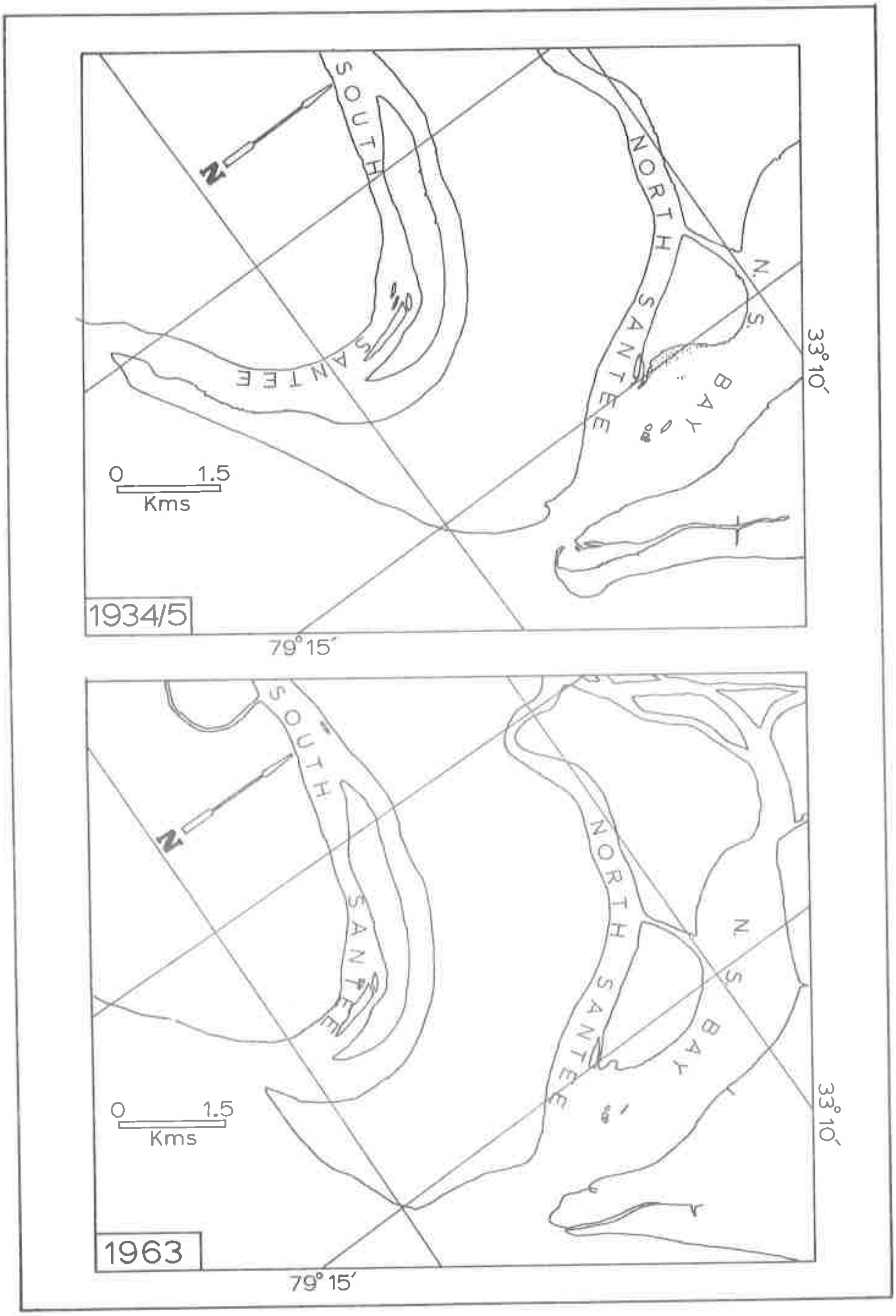

Figure 6. Comparison maps of the Santee River Delta before and after diversion (1942).

These areas of accretion are the only areas that have had their cross-sectional areas significantly reduced. On rediversion, erosion or scouring is inevitable until volume is in equilibrium with cross-sectional area. The channels could be widened but this is not as efficient as increasing their depth (Bates, 1953). Also, widening of the channels, especially near the ocean, would be extremely difficult because of the presence of man-made levees which flank the river system.

Hydrologically, the Santee system should revert to a salt-wedge type estuary. However, the shallowness of the system could prevent the salt-wedge from penetrating very far inland, probably no greater than 4-5 kilometers.

Rediversion of the Santee River therefore, will probably result in the reestablishment of the old river channel except in areas where the marine sands have decreased the water depth significantly. In these areas sedimentary infill may be great enough to inhibit the reestablishment of former channels. This may result in the river "jumping" its channel, eroding present land area, and establishing new channels.

SUMMARY AND CONCLUSIONS

Diversion of the waters of the Santee River into the Cooper River changed the hydrological and sedimentological parameters of the Santee River Estuaries. The estuaries changed from salt-wedge stratified estuaries to partially mixed estuaries.

Diversion increased the importance of the marine environment in the proximate areas of the mouths. The beaches have been modified and shoved landward exposing back-barrier environments seaward of the beaches. Marine sands have been transported into the mouths of the estuaries and into the channels inland from the mouths and have effectively plugged the mouths.

Upon rediversion the system will revert to a salt-wedge stratified estuary. Rediversion will probably alter existing channel configuration especially in areas close to the mouths where the marine sands have been deposited.

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DEPENDENCE OF TENSILE STRENGTH ON FLUID PENETRATION IN THE WINNSBORO GRANITE

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ABSTRACT

Pinching-off experiments were performed in three mutually perpendicular directions normal to the common quarry-fracture directions in the Winnsboro granite. These experiments were performed at room temperature to test the effects of differing pressurization rates and different fluid viscosities upon the tensile strength of a permeable rock in pinching-off tests. Unjacketed cores were stressed to failure at different pressurization rates in both oil and water. Cores tested at rapid pressurization rates showed a strong dependence of tensile strength on fluid penetration.

At a given pressurization rate, this fluid penetration was in turn governed by the viscosity of the fluid utilized. The cores observed at slower pressurization rates demonstrated complete fluid penetration and a reduced dependence of tensile strength upon the pressurization rate and fluid viscosity. Anisotropy observed in tensile strength is thought to be a consequence of directional variation in microfracture length. The relative values of tensile strengths agree within 14 percent with the relative strengths predicted from flaw length measurements obtained from thin sections. This result supports the Griffith criteria of failure.

INTRODUCTION

In recent years geologists have developed an interest in the response of rock to tensile stress. Some joints may be a type of natural hydraulic fracture that develops in rocks when the internal pore pressure exceeds the magnitude of the least external principal stress, thereby resulting in a state of effective tension (Secor, 1965, 1968). The fluid supplying this pore pressure may be liberated naturally by the solidification of volatile magmas, diagenetic changes in sediments, or

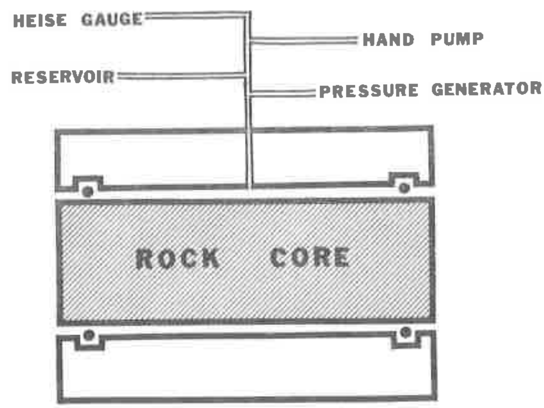

Figure 1. Schematic of the experimental apparatus with a cross-section of the pinching-off sleeve and the cylindrical sample. Pressure seals are made by o-rings at the ends of the sleeve.

decomposition of hydrous minerals. High pore pressures can also be artificially attained when fluid is injected underground in waste disposal projects, during oil field operations, in earthquake modification experiments, or during attempts to recover geothermal energy from hot dry rock.

In order to construct realistic models for the above processes, it is necessary to know how rock reacts to effective tensile stress. One convenient way to obtain this information is to test rock cores under controlled conditions in the laboratory. Traditionally tensile strength tests have been performed by point loading or mechanical end loading (Jaeger and Cook, 1969). However, it is difficult to adapt the specimens of either method for use with a pressurized pore fluid. A third type of test, the "pinching-off" experiment (Figure 1), can be regarded as a type of tension testing if the sample is permeable enough to permit the pressurizing fluid to penetrate throughout the rock core (Hubbert and Rubey, 1961).

Pinching-off testing is a process in which a cylindrical specimen is radially stressed to failure in a hydraulic fluid. This process was named for the tendency of ductile metal samples to neck down or "pinch-off" prior to failure (Bridgman, 1912). Pinching-off testing was chosen for this study since it provides a means of observing the behavior of rock in the presence of a pressurized fluid, a condition which approaches natural conditions at shallow crustal depth. This method has the advantage of generating no bending moments in the specimen, while producing repeatable strength values ($\pm$ 3%). The one disadvantage is that each experiment must be performed at a pressurization rate slow enough to obtain complete fluid penetration of the core. If penetration is incomplete, the apparent tensile strength exceeds the actual value.

Jaeger (1963) and Jaeger and Cook (1963) were the first to perform pinching-off experiments on rock. They tested dolerite, marble and quartzite samples, using oil as the hydraulic fluid. Some samples were jacketed in copper while others were unjacketed. When using unjacketed samples of these highly impermeable rocks, they noticed that use of water or oil as a fluid did not produce a difference in breaking pressure. Both Jaeger and Cook appreciated the importance of penetration, but did not systematically investigate the effects of varying degrees of penetration on tensile strength, and performed their tests at a fixed pressurization rate of 38.8 x 10^{-4} bars/sec.

The work described in the present paper was performed to test the effects of differing pressurization rates upon the tensile strength observed in pinching-off. The lowest pressurization rate in this study was 10^{-4} bar/sec which comes closer than Jaeger and Cook's fixed rate of 38.8 x 10^{-4} bars/sec. to approaching naturally occurring rates of stress change. This study then proceeds to observe the relationship between the mechanical strength anisotropy and the geometry of the internal microfracture length.

Acknowledgments

The authors would like to acknowledge the cooperation of the Winnsboro Blue Granite Corporation of Rion, S. C. for donating the rock used in this study. We are grateful to A. E. M. Nairn, P. Talwani and W. E. Sharp for their assistance with the manuscript.

THE WINNSBORO GRANITE

Winnsboro granite was chosen for these experiments because of its homogeneity and local availability, and because preliminary tests indicated that consistently repeatable values of tensile strength could be obtained from this rock type. The "Winnsboro Blue Granite" is the trade name for the Paleozoic Rion Adamellite, a member of the Winnsboro Igneous Complex (Kesler, 1936; Overstreet and Bell, 1965; Wagener, 1970a, 1970b) that crops out in Fairfield County, South Carolina (Figure 2).

The Winnsboro Granite (Wagener, 1970b; Witkus, 1973) consists of the major minerals: quartz, microcline perthite, plagioclase and biotite. It has an equigranular texture with a maximum grain size of 0.5 to 5.0 mm. In some places phenocrysts up to 10 mm in length are present, however these were not observed in the cores used in these experiments. No mineral layering or flow banding was evident in the experimental material, and the mineral components show little or no preferred orientation.

Like most granitic rocks, the Winnsboro exhibits three orthogonal quarry fracture directions. These are referred to as the rift,

Figure 2. Location of Anderson Quarry in Fairfield County, S. C. Shaded area is Fairfield County.

grain and hardway in order of ease of splitting. The irregularity of the fracture surface is greatest in the hardway direction, and least in the rift direction. Following Peng and Johnson (1972), R, G, and H are used to refer to the axial directions of the cores taken normal to the rift, grain and hardway planes respectively.

EXPERIMENTAL PROCEDURE

Bridgman (1912) did pioneering work on the pinching-off effect in glass and metal samples. Gurney and Rowe (1945a, 1945b) also used pinching-off to examine the behavior of plastics. Jaeger and Cook (1963) studied a dolerite, marble and quartzite in both pinching-off and breaking-off tests to compare these types of testing to other modes of failure testing. Jaeger (1963) subsequently pinched-off Tasmanian dolerite in a series of experiments designed to test the law of effective stress.

The results of Jaeger and Cook (1963) document the differences in pinch-off strength between jacketed and unjacketing cores. They found greater strengths (up to 100%) in the unjacketed cores than in identical specimens loaded in a mechanical tensile testing machine, a result in agreement with those of Bridgman (1912). The materials tested, Tasmanian dolerite, Wombeyan marble and Rand quartzite, are highly impermeable, hence little or no difference was noted between cores pressurized in water and oil at 38.8×10^{-4} bars/sec.

In his subsequent work, Jaeger (1963) allowed his samples to equilibrate under hydrostatic conditions before pressurizing to failure at the rate of 3.33 bars/sec. While noting that there are time dependent effects due to penetration, he did not document them. Jaeger postulated that different stresses in the wet and dry portions of rock cores caused differential stresses and possible damage.

The apparatus used in the pinching-off experiments is shown in Figure 1. An unjacketed rock core is enclosed in a metal sleeve with the ends of the core projecting outside the sleeve through o-ring seals. In a typical experiment, the space around the rock core between the o-ring seals is pressurized with water or oil at a constant rate. Since the core is unjacketed, the fluid will progressively penetrate into the rock as the pressure is gradually increased. At a critical pressure, an extension fracture develops perpendicular to the axis of the core, and the two halves are pushed out of the sleeve through the o-rings. Failure generally occurs as a quiet snap following the last pressure increment.

In experiments of this type, the greatest external principal stress is the pressure applied to the cylindrical surface of the sample. This total stress is directed radially inward perpendicular to the core axis. The least external total principal stress acts along the axis of the core and is due to the small frictional resistance of the o-ring seals. According to Jaeger (1963) this resistance is equal to a maximum of 7% of the applied pressure. Tranter and Craggs (1945) have studied the internal stress distribution produced by this type of loading. Areas of high stress concentration occur in the vicinity of the o-ring seals, but these quickly die out along the axis of the core, and the middle half of the core is subjected to a uniform greatest total principal stress (S_1) directed radially inward and equal to the applied pressure. In experiments done at slow pressurization rates, fluid penetrates the pore network of the granite and oozes out the end of the core. The internal pore pressure near the cylindrical surface of the sample and along the axis of the sample midway between the o-ring seals closely approaches the applied pressure (P). The longitudinal effective principal stress (σ_3) in the core will be equal to the difference between the total longitudinal principal stress (S_3) and the pore pressure (P):

$$\sigma_3 = S_3 - P$$

but S_3 is small and due only to the o-ring friction, because the ends of the core are unconfined. Therefore:

$$\sigma_3 \approx -P$$

The failure mode in pinching-off experiments on brittle material should therefore be tension fracturing across the axis of the core perpendicular to the tensile least effective stress.

Pinching-off experiments offer some advantages over more conventional modes of testing. The apparatus is simple and no complex samples shapes or fabrication methods are required. No point loads are generated on the sample surface and the process is not destructive to the failure surface produced. Although stress concentrations occur at the o-ring seals failure almost always occurs near the middle of the core where the stress distribution is uniform.

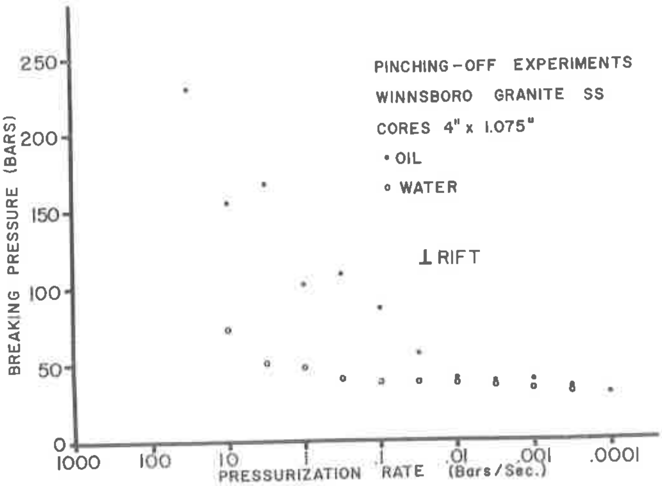

Figure 3. Tensile failure value for cores taken normal to the rift cleavage. Each point represents one core broken in either water or oil. Failure values here are not corrected for o-ring friction.

The effect of varying degrees of fluid penetration were studied in a series of pinching-off tests run on Winnsboro granite cores at pressurization rates ranging from 0.0001 to 100 bars per second. Three groups of approximately 30 cores each were taken parallel to R, G, and H respectively. These cores had a diameter of 1.075 ± 0.004 in. and varied in length from 3.5 to 4.5 in. All cores were degreased by sequential boiling, then drying at 90°C in toluene, xylene and acetone. Dry cores were placed in the pinching-off sleeve and pressurized in one bar increments (where possible) until failure occurred. In one series of experiments, distilled water was used as the pressurizing fluid, and in another series a rather viscous (SAE 10) vacuum pump oil was used.

DISCUSSION OF RESULTS

The results of the pinching-off tests on Winnsboro granite are shown in Figures 3, 4, and 5. Each is a plot of the pressure applied at the time of failure as a function of the rate of pressurization. Each data point in Figure 3 represents a core stressed to failure. Failure always occurred by extension fracturing approximately perpendicular to the axis of the core, and in most cases this fracture was located in the central half of the sample where the stress distribution is uniform.

At rapid rates of pressurization (greater than 1 bar/sec in water and 0.01 bar/sec in oil), the breaking pressure is strongly dependent

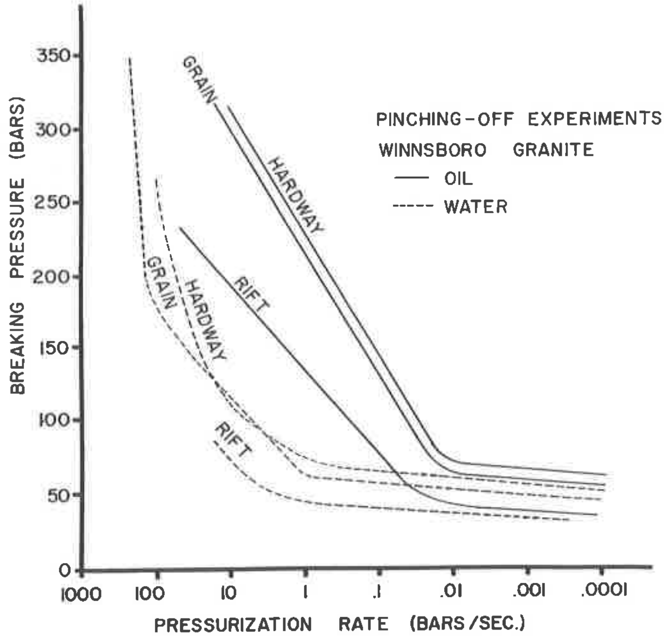

Figure 4. Best-fit curves plotted from the rift, grain and hardway failure values. Correction for o-ring friction would lower these curves by a maximum of 1. 8 bars. Differences in grain and hardway values are not easily distinguished at rapid pressurization rates.

on the rate of pressurization. Examination of these rapidly pressurized samples immediately after failure revealed a dark penetration ring within the exterior surface of the core, whereas the central part of the core was much lighter because the microfractures and grain boundaries were still dry. The pressures at failure on samples run at these rapid pressurization rates show a high degree of scatter (Figure 5) since the penetration observed was highly variable.

The observed degree of penetration progressively increases as the pressurization rates decreases. At pressurization rates slower than 1 bar/sec in water and 0. 01 bar/sec in oil, complete penetration occurred as indicated by fluid seeping from the ends of the cores. With complete penetration, the observed breaking pressure shows a much reduced dependence of pressurization rate. However, this continual slow decline of breaking pressure with pressurization rate is difficult to understand. It may indicate the involvement of some time dependent process in the mechanism of brittle tension fracture, for example the continual decline of breaking pressure may be due to the progressive penetration of very small cracks and pores after the framework of large openings had already been filled with fluid.

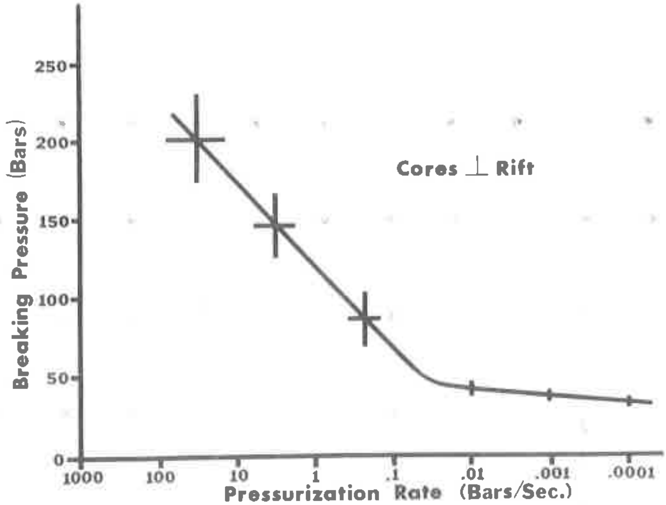

Figure 5. Observed strength variation of rift cores broken in oil. Variation is plotted on the best-fit curve of Figure 4, and ranges from + or -19 bars at 10 bars/sec. to a maximum + or -3 bars on the slow-rate portion of the curve. Water variation was less than one-third of the oil variation and could not be easily depicted.

At all pressurization rates, the breaking pressure using water is less than that when using oil as the fluid. This separation is thought to result from the higher viscosity of the oil which inhibits penetration and effectively shifts the oil points to the right of the water points.

MICROFRACTURE ANALYSIS

The internal crack geometry was decorated by a staining technique (Fryer and Roberts, 1963; Baldridge and Simmons, 1971) which permitted their lengths to be measured in thin sections. The relative ease of splitting along the rift, grain, and hardway (Table 1) seems to correlate qualitatively with the maximum lengths of microfractures aligned along these directions (Figure 6).

Griffith (1921, 1925) devised a theory of rupture in which failure is attributed to the presence of high stress concentrations around the microfractures in a material. This theory has been extended to the three-dimensional case of randomly-oriented penny-shaped cracks by Sack (1946) and by Sneddon (1946), who derived the following formula for tensile strength:

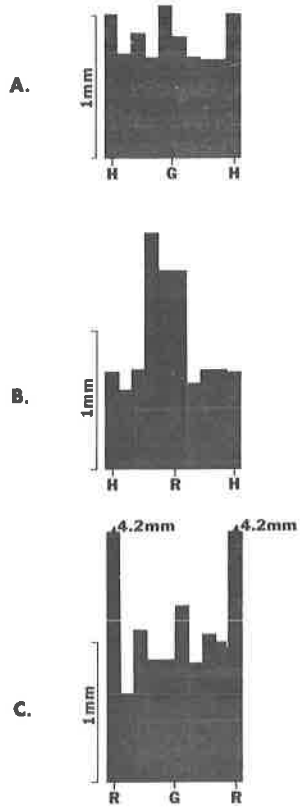

Figure 6. Plot of maximum microfracture length vs. direction in thin sections cut in the following orientations:

A. Parallel to the rift cleavage (251 observations).
B. Parallel to the grain cleavage (122 observations).
C. Parallel to the hardway cleavage (239 observations).

$$K = \left[\frac{\pi E \gamma}{2C(1 - v^2)} \right]^{1/2} \qquad (1)$$

where K is the tensile strength, E is Young's modulus, γ is the energy required to produce unit area of surve, v is Poisson's ratio, and 2C is the crack diameter. No significant preferred orientation of the biotite crystals was observed in the thin sections of this study. The Winnsboro granite shows no foliation or flow banding, and it is assumed that the

Table 1. A comparison (using Equation 2) of observed (K) and predicted (C) tensile strength ratios for cores normal to the rift, grain and hardway planes of Winnsboro granite. Maximum observed microfracture dimensions are AxB, with A greater than B.

OBSERVED STRENGTH RATIOS	Kr/Kh	Kr/Kg	Kg/Kh
1. Observed in pinching-off; Mean value of slow-rate tests in water	.591	.683	.866
Standard deviation of above values	.030	.037	.029
2. Observed in pinching-off; Mean value of slow-rate tests in oil	.545	.607	.896
Standard deviation of above values	.065	.058	.044
PREDICTED STRENGTH RATIOS	$(Ch/Cr)^{1/2}$	$(Cg/Cr)^{1/2}$	$(Ch/Cg)^{1/2}$
3. Predicted from the longest microfractures, with C=A	.483	.555	.870
Predicted for elliptical microfractures, with $C=(AB)^{1/2}$	.563	.669	.842
4. Predicted from the mean of the five longest microfractures	.510	.557	.915
5. Predicted from the longest associated biotite and microfracture length	.845	.926	.913
6. Predicted from the mean of the five longest associated biotite and microfracture lengths	.831	.908	.915

silicate matrix that surrounds the microfractures is isotropic with respect to the elastic properties E, v, and γ. Birch (1960) examined the elastic behavior of various rock types by seismic methods. He subjected the specimens to as high as 10 kilobars hydrostatic pressure to close the existing microfractures. Twelve different granites were included in this study, and all showed less than 3.9% variation in velocity with direction at 10 kilobars hydrostatic pressure. The assumption that the granite matrix is isotropic with respect to these elastic properties is therefore reasonable for a first-order approximation. While the Sack and Sneddon formula was derived for penny-shaped cracks, Johnson (1970, p. 384) states that for a first-order approximation, the exact dimensions of an elliptical crack are not required if the maximum dimension can be ascertained. With all the above assumptions, the ratio of two tensile strengths K_1 and K_2 in two different directions become equal to the reciprocal square root of the corresponding maximum crack radii C_1 and C_2.

$$\frac{K_1}{K_2} = \left[\frac{C_2}{C_1}\right]^{1/2}$$

In Table 1, the observed strength ratio for R, G, and H cores which showed full fluid penetration prior to failure are compared with the corresponding strength ratios predicted from microfracture measurements. Strength ratios are used here to eliminate any time dependent effects which would alter equation 1. The agreement between the observed and predicted strengths ratios is quite good (within 14%).

Since many fractures intersect biotite crystals, it is possible that the weak cleavage of biotite could behave as an active part of a Griffith flaw. Rows 5 and 6 for Table 1 show strength ratios predicted from flaw lengths obtained by adding the coincident length of a mica cleavage to an associated microfracture. The predicted strength ratios thus derived do not agree well with the observed strength ratios. This result suggests that the weak cleavage of biotite is not behaving as a primary Griffith flaw in the Winnsboro granite. Subsequent examination of the biotite crystals under reflected light shows that much of the cleavage surfaces are filled and probably cemented by a secondary iron oxide.

CONCLUSIONS

The effective tensile strength of Winnsboro granite as measured in pinching-off experiments is strongly dependent on the penetration of the pressurizing fluid. In samples showing complete penetration a small dependence of tensile strength on pressurization rate was still observed. The tensile anisotropy of Winnsboro granite, as measured in pinching-off experiments on R, G, and H cores at slow rates of pressurization, seems to be a consequence of internal microfracture anisotropy. The observed relative differences in strength of R, G, and H cores are thus compatible with the Griffith theory of failure.

Experience indicates that pinching-off experiments are a convenient method of measuring the effective tensile strength of rock. However, because of the strong dependence of the apparent strength on penetration, it is necessary to perform the experiments slowly to ensure complete fluid penetration. The pinching-off method may not be applicable to extremely impermeable rock types because inconveniently slow rates of pressurization would be required to obtain complete penetration.

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LOCATION OF CRETACEOUS-TERTIARY BOUNDARY.

DRAWYERS CREEK, DELAWARE

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ABSTRACT

Foraminifera from outcrops and a test hole near Odessa, Delaware were studied to clarify the position of the Cretaceous-Tertiary boundary. Some previous investigations indicate that the boundary might be exposed in outcrops along Drawyers Creek; others suggest that the exposed section is entirely Tertiary. The sparse assemblages obtained in this study are Paleocene. It is concluded that the Cretaceous-Tertiary boundary lies at least 18 meters beneath the lowest available outcrops along Drawyers Creek.

INTRODUCTION

The Hornerstown Formation of New Jersey and Delaware and its stratigraphic equivalents to the south have received considerable study as they either contain or lie very near the Cretaceous-Tertiary boundary, thus affording an opportunity to examine a systemic boundary in detail. As with most units of the Atlantic Coastal Plain, outcrops are limited and both lithostratigraphic and biostratigraphic techniques have been used to trace this horizon. The nomenclature of the Rancocas Group of New Jersey, which contains the Hornerstown and Vincentown Formations, and the extension of the Rancocas into Delaware was described by Jordan (1962a). In the geologic map of the Middletown-Odessa area in Delaware, Pickett and Spoljaric (1971) differentiated the Hornerstown and Vincentown Formations on lithologic grounds and established nomenclature in Delaware that is parallel to usage in the type areas of New Jersey.

In Delaware outcrops of the Hornerstown are located principally along Drawyers Creek north of Odessa (Figure 1). Groot, Jordan, and Richards (1961), Jordan (1962), and Pickett and Spoljaric (1971) have felt that the lithologies present in these exposures represent only the Hornerstown Formation. In addition, they found no evidence for locating

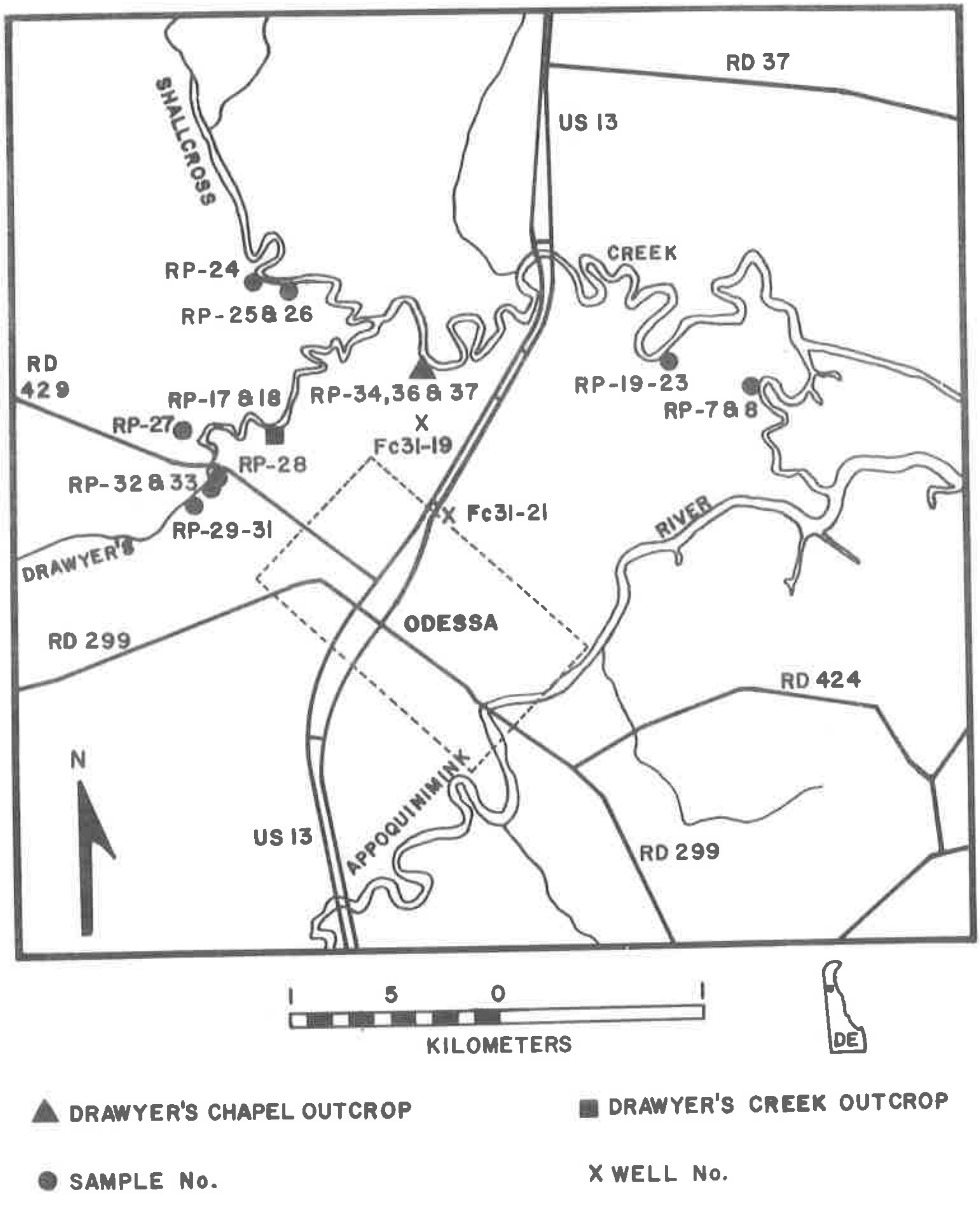


Figure 1. Area of study and sample locations.

the Cretaceous-Tertiary boundary within the exposed section. In contrast, Minard and others (1969), Owens and others (1970), and Owens and Sohl (1973) have interpreted the same sections as containing the Mount Laurel and Hornerstown Formations of Cretaceous and Tertiary ages, respectively.

Previous Investigations

Studies by Jordan and Adams (1962) and Jordan (1962a, b; 1963), which involved mostly the subsurface, produced no clear evidence of an unconformity marking the Cretaceous-Tertiary boundary in Delaware. These investigations and subsequent field work also indicated that the boundary, together with any major unconformity, if present, should be in such a stratigraphic position as to be exposed in, or within several stratigraphic meters of the outcrops along the banks of the Drawyers Creek.

Minard and others (1969) describe a glauconitic quartz sand in the lower 1.2 to 2.4 meters of the south banks of the Drawyers and Shallcross Creeks as the Mount Laurel Formation (Cretaceous) and interpret its contact with the overlying greensand, which is identified as Hornerstown, as an unconformity at the Cretaceous-Tertiary boundary. This view is also held by Owens and others (1970) and Owens and Sohl (1973) who found the lithologies and stratigraphic positions similar to those in New Jersey and warranting the same interpretation. Although no fossils, other than burrows, were reported from the stream bank outcrops, it is of interest to note the potassium-argon date of 63.8 ± 2.1 m.y. obtained from the glauconite at the Drawyers Chapel locality by Owens and Sohl (1973).

In mapping the geology of the Middletown-Odessa, Delaware area Pickett and Spoljaric (1971) considered the entire exposed section in the Drawyers and Shallcross creeks to be Hornerstown. They found the exposed Hornerstown consists of a lower glauconitic sand, a reddish-brown glauconitic quartz sand, and an upper glauconitic sand (Pickett, personal communication). The upper two units are exposed in the Drawyers and Shallcross Creeks and the middle unit appears to be that identified by Minard and others (1969) as the Mount Laurel. Pickett and Spoljaric (1971) concluded that the lower glauconitic unit of the Hornerstown is not exposed and that any interruption of sedimentation discerned in the outcrops is within the Rancocas. The presence of a burrowed contact within the exposed section suggests a local interruption of sedimentation or at least shoaling conditions (Pickett, personal communication). Moreover, lacking body fossil evidence, it was implied that the Cretaceous-Tertiary boundary, insofar as it may relate to lithologic units, lies in the subsurface beneath the outcrops.

Two independent problems exist: the assignment of strata to formations on the basis of lithology; and, the identification of the Cretaceous-Tertiary boundary by paleontological means. The solution of either of these questions will not necessarily solve the other because of the differing criteria of lithostratigraphic and biostratigraphic correlations. This investigation deals with the position of the Cretaceous-Tertiary boundary at Drawyers Creek as indicated by planktonic foraminifera. Resolution of differences in lithostratigraphic nomenclature should be attempted when additional subsurface data bearing on the continuity of rock units becomes available.

Acknowledgments

We are grateful to R. N. Baker whose participation in the early phases of this study while in the Department of Geology, University of Delaware, resulted in the discovery of foraminifera in samples of the Drawyers Chapel outcrop and to T. E. Pickett, Delaware Geological Survey, who critically reviewed the manuscript and offered helpful comments.

The College of Graduate Studies, University of Delaware, provided a grant-in-aid for the necessary drafting and photography.

AREA OF INVESTIGATION AND SAMPLE DESCRIPTIONS

Figure 1 shows the locations of the ten outcrops and one well (Fc31-21) which were sampled for this study. All of the outcrops investigated are in the Hornerstown Formation as described by Pickett and Spoljaric (1971) with the exception of one from the Vincentown (samples RP-7 & 8).

Twenty-three samples were taken from the outcrops. Between 1.3 and 2 kilograms of each sample were washed and floated to separate microfossils. Only 5 samples yielded foraminifera: RP-34, 36, and 37 from near Drawyers Chapel and RP-18 and 19 from an outcrop 1 kilometer upstream.

As shown in Figure 2, RP-34 is 3.7 meters above the contact postulated as the Cretaceous-Tertiary unconformity by Minard and others (1969), Owens and others (1970), and Owens and Sohl (1973). The other two samples from this location are from the reddish-brown glauconitic quartz sand 1.4 and 1.7 meters below its top.

Samples RP-18 and 19 are also from the reddish-brown glauconitic quartz sand. No contact is exposed at this outcrop but would be expected to lie about 0.3 meters above the exposed section based on correlation from other outcrops in the vicinity. If this assumption is correct the samples are from about 1.2 and 2.4 meters, respectively, below the top of the unit.

The only other sample to yield foraminifera was recovered from well Fc31-21 drilled just north of Odessa, from 16.8 meters below sea level and is a glauconitic sand containing some small, unidentifiable fragments of shell.

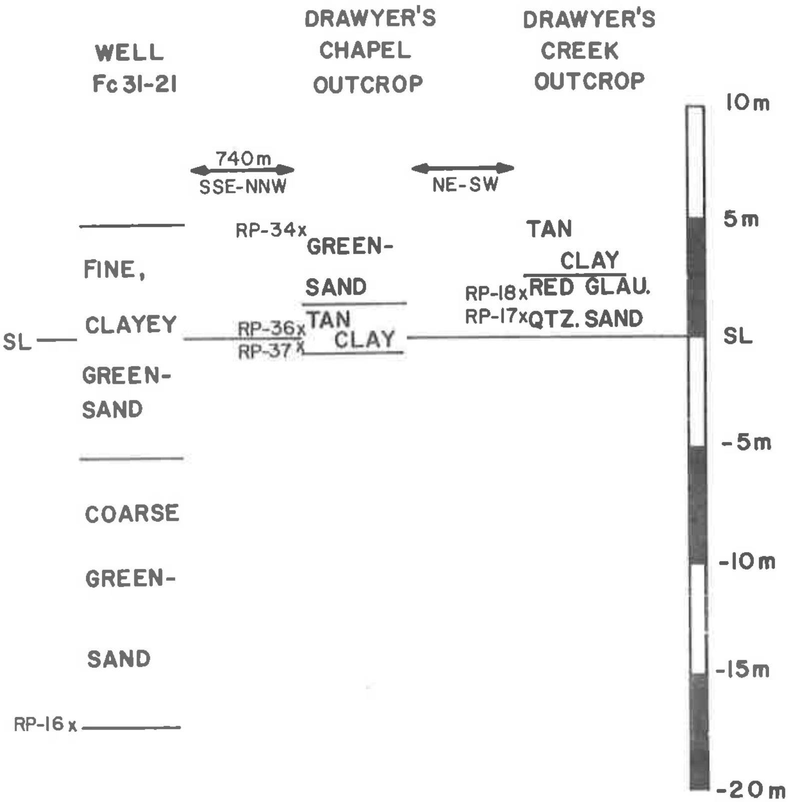


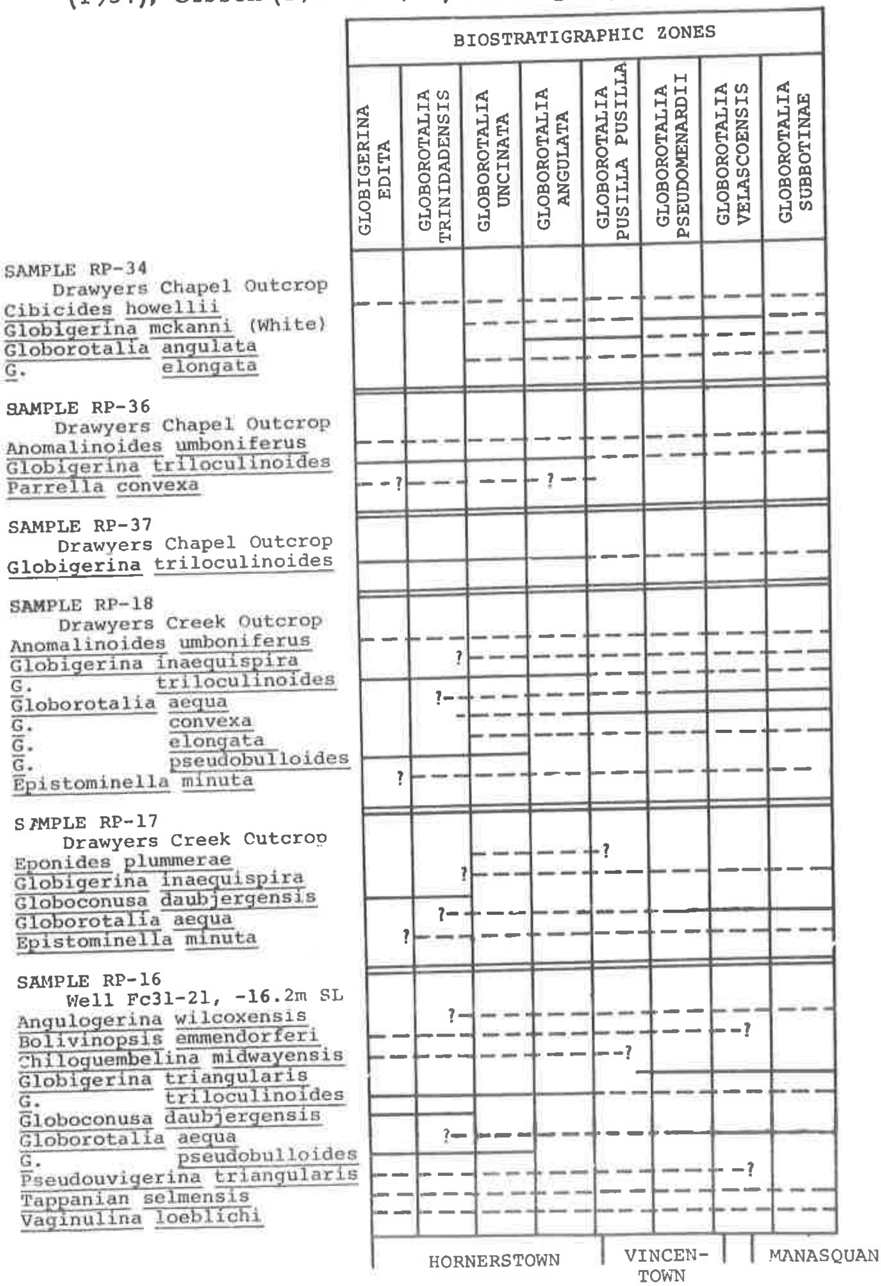
Figure 2. Schematic section along Drawyers Creek, relationships of samples.

RESULTS

The biostratigraphic zones proposed by Olsson (1970) from work in New Jersey are used as a framework for correlating the results of this investigation. Although the Delaware samples yielded only sparse faunas, sufficient microfossils were recovered to establish that the section studied is Tertiary. The ranges of all foraminifera recovered include the Paleocene. The planktonic species identified do not extend into the Cretaceous and the ranges of the benthonic species include portions of the Tertiary as well as the Upper Cretaceous. Because of poor preservation some foraminifera could only be identified to genus; in these cases the generic ranges are also Tertiary.

Table 1 shows the faunal ranges from New Jersey described by Olsson (1970) in solid black lines. The extended ranges shown by dashed lines, have been compiled from other authors working in the Atlantic

Table 1. Species identified in this study compared with biostratigraphic zones of New Jersey from Olsson (1970). Solid lines indicate ranges from Olsson (1970), dashed lines indicate probable ranges from Loeblich & Tappen (1957), Olsson (1960 & 1964) and Nogan (1964).



and Gulf Coastal Plains: Loeblich and Tappen (1957); Olsson (1960, 1964); Nogan (1964).

The youngest fossiliferous sample comes from the Hornerstown greensand at the Drawyers Chapel outcrop (sample RP-34). Three planktonic species, Globigerina mckanni (White), Globorotalia angulata and G. elongata, and one benthonic species Cibicides howelli, were identified. Olsson (1970) reports that the ranges of Globigerina mckanni (White) and Globorotalia angulata just overlap in the lowermost Globorotalia velascoensis zone. Biostratigraphic ranges suggested by other authors indicate overlap for all four species ranging from the Globorotalia angulata to G. subbotinae zones. This would suggest a Landenian to lower Ypresian age for the greensand.

Samples RP-36, 37, and 18 contain a foraminiferal fauna that is older than sample RP-34. Sample RP-36 contains Globigerina triloculinoides and Anomalinoides umboniferus which range from the G. edita to the G. subbotina zones. The range of Paralla convexa is not well known but is within the G. uncinata zone.

Sample RP-37 contained only one species of foraminifera: Globigerina triloculinoides, which occurs in Paleocene to Eocene rocks. Sample RP-18 has a larger fauna than the four other samples examined. The six planktonic species are Globigerina inaequispira, G. triloculinoides, Globorotalia aequa, G. convexa, G. elongata and G. pseudobulloides. These indicate an age restricted to the middle G. trinidadensis to G. uncinata zones. The two benthonic species, Anomalinoides umboniferus and Epistominella minuta (Olsson) have ranges too long to indicate anything other than Paleocene to Eocene.

Sample RP-17 contains the planktonic species Globoconusa daubjergensis, Globigerina inaequispira, and Globorotalia aequa and benthonic species Eponides plummerae and Epistominella minuta (Olsson). The age suggested by this assemblage is upper Globorotalia trinidadensis zone. Unfortunately, the ranges of Eponides plummerae and Globigerina inaequispira are not known well enough to have a well-established lower range.

The last sample to contain Foraminifera, RP-16, comes from 16.8 meters below sea level in well Fc31-21. The six planktonic species, Chiloguembelina midwayensis, Globigerina triangularis, G. triloculinoides, Globoconusa daubjergensis, Globorotalia aequa and G. pseudobulloides, indicate the Globorotalia trinidadensis zone. The five benthonic species are far ranging with overlapping ranges. One species, Tappanina selmensis, ranges from Cretaceous to Tertiary.

DISCUSSION

The outcrops of glauconite and glauconite-quartz sands along Drawyers and Shallcross Creeks in the Odessa area expose two contacts. The upper contact is seen along the upper reaches of Drawyers Creek and separates the Hornerstown Formation from the Columbia Formation rocks of Pleistocene age. The second contact is well exposed at the Drawyers Chapel outcrop and separates a glauconite-quartz sand from the upper glauconite sand.

A sequence of samples across this unconformity has yielded characteristic lower and middle Paleocene (Danian and Landenian) foraminifera. It could be argued that the foraminifera found below the contact represent mixing of the upper greensand unit downward by burrowing organisms. While there are many fossil burrows present in the outcrops the fossil assemblages from the samples represent a progressive time sequence in which mixing does not appear to be important. Also, the recovery of a Danian foraminiferal assemblages from 16.8 meters below sea level 740 meters southwest of the Drawyers Chapel outcrops shows that the Paleocene strata are thick at this point, and places the Cretaceous-Tertiary time line stratigraphically well below the Drawyers Chapel outcrop.

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OLIVINE COMPOSITIONS FROM SOUTHERN APPALACHIAN ULTRAMAFICS

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ABSTRACT

Electron probe microanalysis of olivine from several Southern Appalachian ultramafic bodies revealed: (1) a remarkably constant olivine composition within and between bodies averaging $Fo_{92.4}$; and (2) no intragranular compositional zoning. These data argue for metamorphic recrystallization origin of the present olivine composition, and can be used to support the serpentine - dehydration hypothesis of Carpenter and Phyfer (1969).

INTRODUCTION

Olivine from five ultramafic bodies of the Southern Appalachians was analyzed by electron probe microanalysis in order to determine if compositional variations existed either: (1) within a given grain, (2) between grains in given ultramafic body or (3) between grains from different bodies. Samples were collected from the Day Book and Newdale deposits of Yancey County, N. C., the Holcomb Branch deposit of Madison County, N. C. and the Balsam Gap deposit of Jackson County, N. C.

Each olivine was analyzed for Si, Fe, Mg, Ni and Mn, using the ARL-EMX probe at Virginia Polytechnic Institute and State University. A Margolati olivine standard was used for all elements except nickel, which was compared to a pure nickel standard. The raw data were reduced using an IBM 360 system and a Empdar IV program written by J. Ruckledge and modified by P. H. Ribbe and G. V. Novak. Standard atomic number, fluorescence and absorption corrections were made. All analyses were performed operating at 15 kv and using at least five grains from each sample. In addition, at least five counts were made on different parts of each grain.

We gratefully acknowledge and appreciate the use of the V. P. I. and S. U. equipment. Analyses were made while Phyfer was in residence at V. P. I. and S. U. We also acknowledge the support of National Science Foundation grant GA 4518 to Carpenter and to the University of South Carolina for partial support of this project.

RESULTS AND DISCUSSION

The analyses of olivine, presented in Table 1, show that all the olivine is remarkably similar in composition. Furthermore, no detectable compositional zoning was exhibited by any of the grains, and no significant variations exist within a given body (Day Book) or between bodies.

Virtually identical olivine compositions throughout other alpine ultramafics are common; see for example the data from the Burro Mt. complex (Loney, et. al., 1971). This pattern of consistent compositions is generally attributed to metamorphic recrystallization. It would be very difficult, in fact, to attribute this composition pattern to any igneous process. Olivine compositions in ultramafic rocks of undoubted igneous origin, e. g., stratiform complexes like Stillwater, vary from layer to layer. For the Southern Appalachian ultramafics to be primary igneous, they would have to represent single, isolated tectonically disrupted layers.

The compositional similarity between olivines from geographically separated deposits further argues for metamorphic recrystallization. Partitioning of iron and magnesium between co-occurring olivine and disseminated chromite suggest that several of the Southern Appalachian ultramafics have reequilibrated at a temperature of no greater than 1000°C (Fletcher and Carpenter, 1972). We do not understand all the implications of these data, especially when the Burro Mt. olivine-disseminated chromite data also indicate equilibration at approximately the same temperature. It would be interesting to examine olivine - disseminated chromite data from all "alpine" type ultramafics to see if this pattern of temperature equilibration holds world-wide.

A metamorphic petrogenesis for these rocks is also supported by petrofabric data which show that olivine from the Southern Appalachian ultramafics (Day Book, Balsam Gap and Dark Ridge) exhibit no preferred orientation and no cataclastic textures (Astwood, Carpenter and Sharp, 1972; Neuhauser, 1974). These data differ from petrofabric and texture data from other alpine ultramafics, however which exhibit preferred olivine orientation and cataclastic textures (Raleigh, 1965; Ave Lallemant, 1967) Astwood, et. al., (1972) suggest that the Southern Appalachian olivine fabric data can only be explained in terms of the serpentine - dehydration hypothesis of Carpenter and Phyfer (1969).

Table 1. Olivine Compositions.

	Day Book 1	Day Book 6	Day Book 7	Day Book 12	Balsam Gap	Newdale	Holcomb Branch
SiO_2	40.94	40.43	40.74	40.88	41.11	40.71	41.31
MgO	49.70	50.17	50.19	49.96	49.59	49.85	50.95
FeO	7.78	7.27	7.12	7.15	7.33	7.11	7.80
NiO	0.44	0.43	0.40	0.43	0.43	0.41	0.43
MnO	0.11	0.10	0.10	0.10	0.11	0.11	0.12
				ATOMS PER 24 OXYGENS			
Si	6.03	5.98	6.01	6.03	6.06	6.03	5.99
Mg	10.91	11.07	11.04	10.99	10.90	11.02	11.01
Fe	0.96	0.90	0.88	0.88	0.91	0.88	0.95
Ni	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Mu	0.01	0.01	0.01	0.01	0.01	0.01	0.01
% Fo	92.0	92.5	92.5	92.6	92.5	92.5	92.2

Although the data presented in this paper taken by themself do not support or refute any of the many existing hypotheses concerning the origin and emplacement of alpine ultramafic rocks, they are compatible with the serpentine - dehydration of Carpenter and Phyfer (1969) when examined in conjunction with other geochemical, petrographic and structural data recently reported by Carpenter and his associates.

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FRACTURE PATTERNS OF THE YELLOW CREEK AREA, MISSISSIPPI

By

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ABSTRACT

A fracture pattern analysis in the Yellow Creek area, in northeastern Mississippi, reveals two dominant trends, N54°W ± 5° and N38°E ± 5°. The data presented suggest that joints were derived from the stress that produced the Pascola Arch rather than the Mississippi Embayment Region.

INTRODUCTION

The Yellow Creek Embayment of Pickwick Lake lies near the eastern line of the Mississippi Embayment Region in the northeastern corner of the state of Mississippi (Figure 1). To the northeast and northwest of the study area, the Pascola Arch is located between the two prominent granitic structures, the Nashville Dome and the Ozark Dome, respectively (Figure 1). The arch is presently covered by approximately 3,000' of Cretaceous-Tertiary unconsolidated clastic sediments.

Acknowledgments

The author wishes to express his appreciation to W. P. Staub of the Geology Department at the University of Tennessee, Knoxville, Tennessee, and to Virginia A. Langenheim of the U. S. Geological Survey, Menlo Park, California, for suggestions and criticism of the report. Also, John M. Kellberg and his colleagues at the Geologic Branch of the Tennessee Valley Authority were helpful in providing information pertaining to the geology of the Yellow Creek area and for the use of the TVA facilities. Funds for this project were provided by the TVA. Permission to publish this material has been given by the TVA and is gratefully acknowledged.

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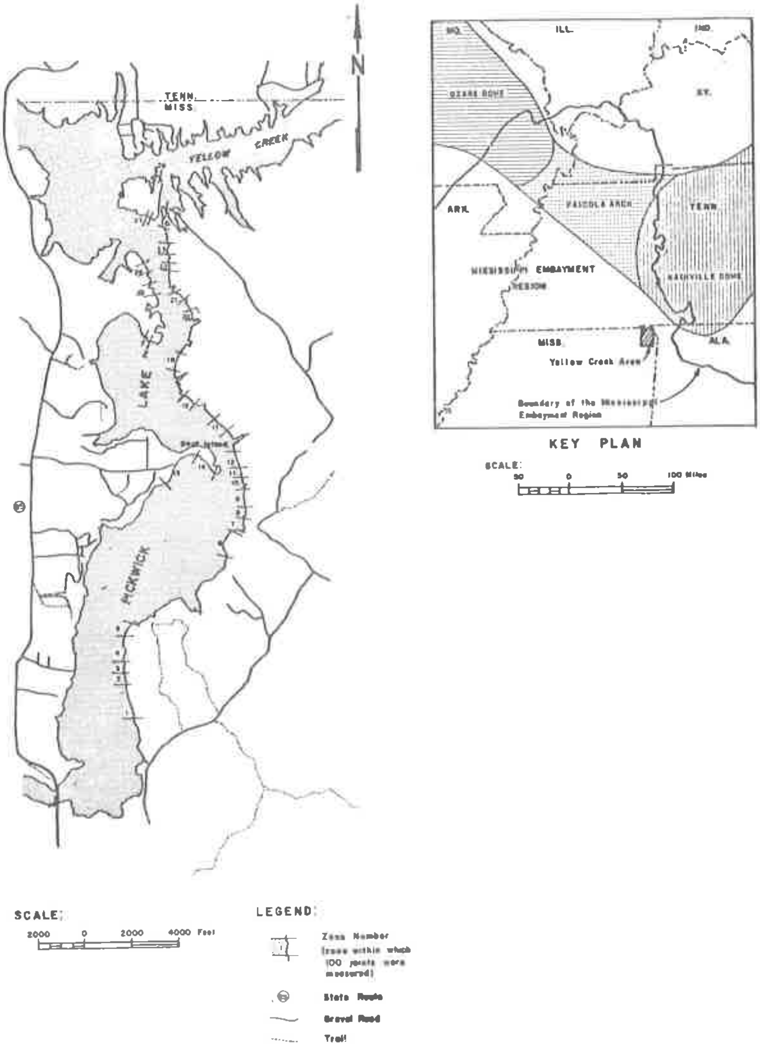

Figure 1. Location map of the Yellow Creek area, Mississippi.

GEOLOGY

The geology of the Yellow Creek area was compiled from the TVA (1971) preliminary report.

The only Paleozoic exposures in the area are the Fort Payne (Upper Mississippian) siltstone and chert. Most strata appear to be horizontal with the exception of a few exposures along the Goat Island shoreland. The Fort Payne Formation is overlain by 50 to 200 feet of unconsolidated Cretaceous-Tertiary clastic sediments. Two dominant trends -- N54°W $\pm$ 5° and N34°E $\pm$ 5° of joints were measured in the Pickwick Landing Dam, about 5 miles north of the Yellow Creek Embayment (Rose, 1940). However, Rose did not discuss the stress components that produced these joint patterns.

FIELD WORK

The survey was done during the summer of 1971. The strike and dip of 100 joints was measured at each station. There was no limit to the size of exposure considered at one location. Where joints were widely spaced it was necessary to take measurements along a breadth of exposure several hundred feet wide. All the joint measurements were taken along the shore of the Yellow Creek Embayment where excellent exposures of the Paleozoic strata are present.

STEREOGRAPHIC PROJECTIONS

An equal area (Schmidt) stereonet was used to illustrate the predominant strike and dip of the 100 measured joints at each station. If a large number of points cluster about the circumference of the net, the predominant dip of the joints is vertical. On the other hand, if points cluster about the center, the dip is horizontal. The simplest way to interpret the stereonet is by mentally substituting a strike-dip symbol for the cluster of points (see key, Figure 2). The dip is toward the center of the stereonet while the strike is at a right angle to dip. For example, if points cluster in the upper right (northeast) quadrant, the predominant strike direction is northwest, and the dip direction is southwest. The percentage of points plotting within a one percent area of the stereonet is contoured to illustrate where the largest number of points is concentrated.

Twenty-eight stereonets (one for each station) are illustrated. The number directly below each diagram identifies the station which is located on map in Figure 1. A four percent contour interval is used. The highest concentration of points is indicated by solid black. The summary stereonet at the bottom represents the maxima from all 28 stations.

In an exposure, both the strike and dip can be measured accurately; however, in stream beds the dip was difficult to measure; whereas in vertical cliffs the strike was difficult to measure. Nevertheless, such measurements deviated only slightly about a mean value.

RESULTS

In the summary stereonet (Figure 2), the results show that

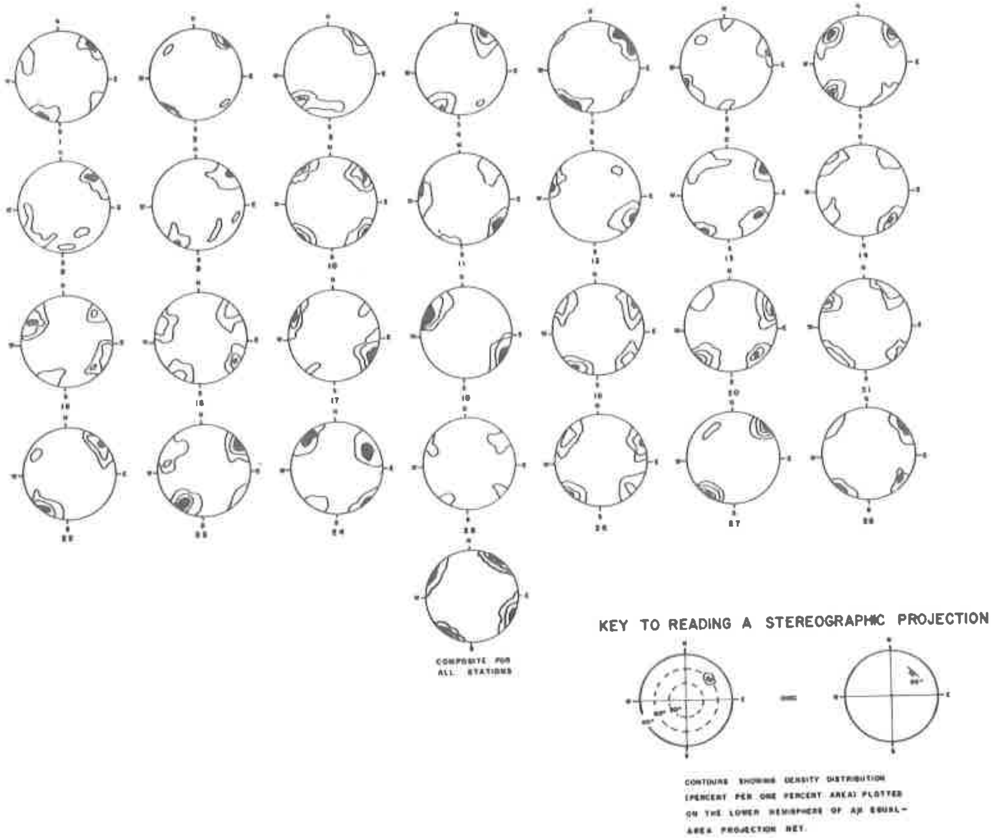

Figure 2. Joint plane orientations in the Yellow Creek area, Mississippi.

joints have strong trends at N54°W $\pm$ 5° and at N38°E $\pm$ 5°. Also, the dip is approximately vertical except as indicated below. Obviously, all stations except 12 and 18 have N54°W $\pm$ 5° trends and all stations except 3, 4, 6, 8, 9, 22, and 27 have N38°E $\pm$ 5° trends. However, the dip of the N38°E $\pm$ 5° trend is not vertical at stations 2, 7, 13, 14, 15, 16, 20, 21, 27, and 28. No particular dip trend is apparent for the nonvertical joints. Thus the dominant trends are closely related to those proposed by Rose (1940).

CONCLUSION

Joint patterns in the area appear to be related to the Pascola Arch whose axis strikes N51°W (Grohskopf, 1955). The results of this survey indicate two dominant strike directions for joints in the Yellow Creek region, 1) N54°W $\pm$ 5° and 2) N38°E $\pm$ 5°, the latter being approximately perpendicular to the former. Therefore, the joint patterns are approximately parallel and perpendicular to the axis of the Pascola Arch. Where joint patterns are related to an arch in the above manner, they are referred to as release joints (Billings, 1954; Price, 1966). If these joints were indeed caused by stress that produced the Pascola Arch, they cannot be related to present tectonic activity in the Mississippi Embayment.

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EVALUATION OF TEXTURAL PARAMETERS AS BEACH-DUNE ENVIRONMENTAL DISCRIMINATORS ALONG THE OUTER BANKS BARRIER, NORTH CAROLINA: A DISCUSSION

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Shideler (1974), in a recent article, stated that his study was done to evaluate the effectiveness of various textural parameters as discriminators in the differentiation of dune, berm, and foreshore sands. But the article does not give convincing evidence to support his contention.

On page 205, he said that the samples were sieved using a Ro-Tap for ten minutes. He has overlooked the classical article by Mizutani (1963) on the effectiveness of sieving with time. Mizutani showed both from experimental and theoretical investigations that it requires at least 30 minutes sieving in order to obtain 95 percent accuracy (page 14). From Mizutani's results, it is clearly seen that any sample sieved for only ten minutes gives an accuracy of not more than 52 percent which is far from satisfactory and not useful for further calculations. Moreover, if sieving time is short, smaller particles still remain above coarser sieves and the fine fractions may not show their true original weight in the final result. Incomplete sieving can produce important effects on the size frequency of the sediment. Mizutani gave numerous examples to show how a well sorted sediment can appear ill sorted in analysis after insufficient sieving time. The variation of the bimodality is clearly visible and the sorting becomes either better or worse than the original sorting.

Shideler has not indicated whether corrections were made in the final size distribution data, to include the gravel size particles which were removed earlier, as well as the shell fragments which were included in the sieving. If these corrections have not been taken into consideration, it is clearly possible that a certain amount of bias has been introduced in the distribution as a whole. He has also not mentioned whether the particles between -1 phi and 0 phi were thrown out, or whether they were sieved through the in-between screens, or whether they were all caught in the 0 phi screen. Any of the above leads to a truncated or censored coarse end, and the moment measures he has employed using these distributions become as bad as parameters of open-ended distributions. This has an especially important bearing, unlike in the case of the graphic measures, on the third and fourth measures. Shideler has also not evaluated the effects possibly introduced by the delay in his sampling in the northern part of his area. With a high to moderate energy environment, as in the Outer Banks, any sampling delay can introduce changes in the sediment distribution as the entire coast is undergoing constant change. Hence, it is not valid to include the statistical parameters obtained from these distributions with the others which were sampled at a different time.

Dune field inclusion ratios were developed from parabolic curves drawn by the author himself. In the strictest statistical sense quite a good amount of bias can be introduced when the author overlooks some of the points not suitable for his pre-conceived conclusions. The dune field inclusion ratio says nothing of the samples mislocated. If the percentage of beach samples is zero the ratio goes to infinity.

The drawing of the curves has no theoretical basis. It is completely subjective and not supported by any logic or reasoning. The parabolic curves are actually not parabolas, but crude hand-drawn U-shaped curves, that are mathematically complicated. Similar curves can be drawn for all plots for which all dune field inclusion ratios are infinity, simply by excluding all beach samples (J. P. May, personal communication).

Discussing his results, Shideler indicated that there is no effective separation on the plots between the foreshore and the berm. On the contrary, redrawing of the graphs (such as those on page 208) indicates that it is possible to arrive at another so-called parabola for each graph that can differentiate between berm and foreshore with a foreshore inclusion ratio of 5.50. As stated above, this has no meaning, Furthermore, a linear trend can also be seen among the foreshore samples. In this connection it has been shown by Stapor and Tanner (1973) and Friedman (1973) that variation in sorting systematically separates dune sands from those of the swash zone. Stapor and Tanner (1973) have also shown that skewness is the most important moment measure entering the discriminant function in this kind of separation.

Shideler has not given any data to prove his contention that one measure is a better discriminant than another, though the graphs clearly reveal (on redrawing) that there is a good amount of differentiation possible between berm and foreshore. His analytical techniques are wrong, which in turn leads to wrong interpretation and conclusions. His conclusions can be only tentative and his interpretations do not support the claims he has made from his data and hence should not be taken into consideration seriously for further reference.

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EVALUATION OF TEXTURAL PARAMETERS AS BEACH-DUNE ENVIRONMENTAL DISCRIMINATORS ALONG THE OUTER BANKS BARRIER, NORTH CAROLINA: A REPLY TO R. S. MURALI'S DISCUSSION

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The highly critical discussion by R. S. Murali of my recent article on textural discriminators (Shideler, 1974) warrants a reply. In essence, he has stated that my conclusions are invalid because the analytical techniques were "wrong". Although Murali's critique has impressed the writer as being largely argumentative in substance, perhaps it can serve a useful purpose by at least providing this opportunity for some much-needed discussion regarding some of the analytical procedures employed by various workers in evaluating textural parameters as environmental discriminators. Therefore, in replying to Murali's specific comments, the writer will also take this opportunity to express his views regarding the critical need for a standardization of procedures employed by the various workers involved in this particular area of research.

Murali's first major criticism concerned my selection of a 10-minute sieving period. He cites Mitzutani's (1963) work which indicated that at least 30 minutes are required for effective sieving (95 percent accuracy). He then makes the rather simplistic statement that 10-minute sieve analyses are essentially useless. If this premise were accepted, we would be obliged to invalidate much of the previous work in the literature, since by consensus, a 10-minute sieving period has long been considered an adequate standard (e. g. Krumbein and Pettijohn, 1938; Twenhofel and Tyler, 1941). This consensus has been discussed by Royse (1970, p. 14-17), and still appears to be in effect. Most experienced sedimentologists realize that sieving is a complex probabalistic process, the efficiency of which is reliant not only upon

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sieving time, but also upon a host of other variables such as sample size, particle size distribution, particle shape, sieve interval, room humidity, and the amount of electrostatic charges on individual grains. Consequently, there is no universally "right" sieving time for all analyses, other than what the circumstances of a particular study dictate. In the study under discussion, the writer desired not only to obtain size analyses that would adaquately denote textural differences among the studied sand populations, but also to produce results that would be comparable with results obtained by a majority of other workers. Both these objectives could be accomplished with a 10-minute sieving period. The adequacy of a 10-minute period was indicated by McManus (1965, p. 794), who observed that this period corresponds to a sieving rate (2.0Ø sieve) of only 0.3 percent total sample per minute. He further observed that the amount of "finer near-mesh particles" is lessened by only 0.5 percent of the initial sample weight per minute thereafter. On the basis of this low rate, McManus suggested that further sieving would not appreciably lessen the number of retained finer near-mesh particles. These results were found to be independent of load size, and although they are strictly applicable to 3-inch sieves, the writer knows of no compelling reason to suspect that the results would not also be generally applicable to the standard 8-inch sieves used in the present study. Although the minimal 35-minute period recommended by Mitzutani (1963) would certainly have increased sieving efficiency, the results would have been comparable with results from only a small minority of workers. In essence, the consensus of a 10-minute sieving period, in itself, is justification for its usage in the present study. Incidentally, overall sieving efficiency in the present study was substantially increased by conducting the 0.25Ø analyses with two successive sieve stacks on the Ro-Tap, each running for a 10-minute period. In effect, the original 50-60 gram sample load was substantially reduced on the second stack of finer-mesh sieves, thus increasing their efficiency (McManus, 1965). The foregoing discussion points out the need for standardized sieving techniques among individual workers, so that comparable results may be obtained in evaluating textural parameters as environmental discriminators.

Another comment made by Murali concerned the possible introduction of bias into the size distributions during analysis. Consequently, more details regarding the employed analytical procedures appear to be warranted. The beach and dune populations indigenous to the studied sector of the Outer Banks range in mean size from coarse to fine sand, and generally contain only sparse admixtures of gravel (shells and inorganics) and silt-clay fractions. For these particular sediments, it was decided that the optimum procedure was to remove all gravel from the samples prior to size analysis of the remaining portion. It was felt that inclusion of the gravel fraction would exert an excessive and misleading influence on the moment measures. The fortuitous occurrence of a few quartz pebbles or a large molluscan shell fragment within a 50-60 gram work sample would result in misleading polymodal distributions. As noted by Friedman (1967), such distributions with coarse modes are notorious for producing inconsistent and unreliable moment measures, especially for sensitive skewness values. Consequently, it was felt that the sub-gravel fraction should be analysed in its "pure state"; thus, the gravel fraction provided data only in terms of the maximum particle size, which approximates Passega's (1957) one-percentile measure. Although the foregoing procedure admittedly truncated the total distribution at the gravel-sand class limit, this was considered the lesser of the two evils. In analyzing the sub-gravel fractions, a preliminary inspection indicated that modal diameters in the majority of samples tended to cluster within the medium sand range, with only relatively small percentages of grains falling within the 0.0ø to -1.0ø and < 4.0ø ranges. Consequently, from a practical standpoint, all grains within the 0.0ø to -1.0ø range were caught on the 0.0ø sieve and weighed collectively; a 0.25ø analysis within this particular size range simply did not appear warranted. The < 4.0ø pan fraction was collectively considered as 4.25ø, similar to the procedure used by Friedman (1961, 1967). It should be noted that Friedman (1967) investigated the accentuated influence of the < 4.0ø pan fraction by also treating it as 6.0ø for movement measure computations. Although differences in absolute values were noted, he did not observe any significant difference in the effectiveness of differentiating beach and river sands on scatter plots. This observation has bearing on the matter under discussion because it suggests that censoring the tails of a size distribution, *per se*, does not significantly affect a moment measure's discriminating ability. Although the analytical procedures employed in this study may have "biased" the size distributions, the significant factor is that the bias was systematically and consistently introduced into all comparative foreshore, berm, and dune samples. Consequently, although absolute moment measure values may have been modified from their pre-analysis state, any genetically significant differences in relative values should have been consistently reproduced and reflected by the scatter diagrams. A major obstacle in the worldwide evaluation of discriminators is not necessarily the introduction of bias, in itself, but rather the inconsistent introduction of various types of bias by individual workers. In fact, one of this study's conclusions (p. 220) is that the utility of the highly sensitive skewness and kurtosis measures is self-limiting because of their relatively high susceptibility to the acquisition of individual bias induced either by analytical procedures, sampling techniques, or local geologic conditions. Although several workers have indeed demonstrated that skewness is an environmentally sensitive parameter, it is this writer's contention that it is also one of the most easily manipulated parameters, and is therefore of lower reliability than some of the less sensitive measures. In making worldwide comparisons involving skewness or kurtosis values, the standardization of sampling and analytical procedures is essential.

Regarding Murali's comment on the short sampling delay in the northern sector of the study area, he contends that it is invalid to group the statistical parameters of those 10 northern samples with the parameters of the other samples obtained a few weeks earlier. This line of reasoning would not only appear to invalidate much of the previous fine work by investigators such as Friedman (1961, 1967), who collectively compared samples obtained from worldwide localities, but it would also preclude one of the major objectives in developing textural discriminators, namely, their potential utility in the recognition of paleoenvironments. If textural discriminators of only precisely synoptic samples can be utilized, how could they ever be applied to ancient deposits contained within the stratigraphic record? Incidentally, it should be emphasized that the present study was not concerned with the textural characteristics of a single sedimentation unit. On the contrary, it was concerned with the average characteristics of several sedimentation units contained within a 5.5 inch channel sample. Consequently, the samples when first obtained, already reflected textural responses integrated over a significant time interval. It was felt that channel samples would provide a rigorous set of test conditions. In addition, they would also represent a pragmatic approach, since geologists working with subsurface well samples frequently are not afforded the luxury of sampling individual sedimentation units.

Lastly, Murali criticized the use of my hand-drawn parabolic curves and their associated dune field inclusion ratios; however, he apparently missed the significant point regarding their usage. It was acknowledged (p. 205) that no theoretical basis existed for using the parabolic-shaped curves, and that any geometric form could be employed if it provided effective separation. The significant factor is that some consistent variety of curve be used as a comparison standard in delineating environmental fields, and that the effectiveness of the fields be quantified in some manner. Although this procedure admittedly still contains some subjectivity, the amount is substantially reduced in comparison with some of the previously used techniques that have resulted in a wide variety of grotesquely-shaped environmental fields. The dune inclusion ratio used in this study is only one of many possible expressions for quantifying the effectiveness of environmental fields. However, as pointed out by Murali, it is indeed possible to circumvent the intent of the inclusion ratio simply by constructing the parabolic curve in such a manner so as to exclude all beach samples; this would result in a perfect dune environmental field mathematically (infinity value), although its utility would be negligible. In an effort to discourage such devious practices, the optimum dune environmental field is here redefined as "the field enclosed within a parabolic curve that best encompasses the maximum number of dune samples while simultaneously minimizing the number of included beach samples, and which encloses a minimal two-thirds of the plotted dune samples". Perhaps this more restricted definition would discourage some unfortunate irrational soul from employing the devious and pointless tactic outlined by Murali. At any rate, the specific quantitative expression used for evaluating environmental fields is really immaterial. The important factor is the need for a consistent method of both establishing and evaluating environmental fields.

In summation, although Murali's critique is largely argumentative in substance, it has provided an opportunity for discussing some important aspects of evaluating environmental discriminators. The main objective of this reply was to stress the need for a standardization of procedures employed by the numerous workers in this particular area of research. In response to Murali's closing paragraph, he states that my analytical techniques are "wrong", but he neglects to present the "right" techniques. In ending the discussion on a philosophical note, this writer considers the "right" analytical techniques to be those which are not only based on idealistic concepts, but which are also tempered by pragmatic considerations, and flexible enough to accommodate a wide spectrum of varying circumstances. Lastly, the writer detects an element of philosophic humor in the naivete of Murali's last remark that my conclusions can be only "tentative". With possible exception of a few individuals gifted with divine insight, what scientist's conclusions are not regarded as "tentative"? In our present knowledge explosion, it is becoming axiomatic that the "fact" of today frequently becomes the "fiction" of tomorrow. Is it not the intrinsic duty of the scientist to constantly refine or modify his "tentative" conclusions, either on the basis of additional data or alternate analytical procedures? The essence of the scientific process is the formulation of progressively closer approximations to the truth, an ever-elusive commodity which may, in reality, be ultimately unobtainable.

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